FINAL REPORT

Flexible Reactive Berm (FRBerm) for Removal of Heavy Metals from Runoff Water

ESTCP Project ER-201213

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14. ABSTRACT
Small arms firing ranges (SAFRs) located on Department of Defense (DoD) facilities are, in many cases, constructed next to wetland areas, including ponds, lakes, and streams. These wetlands, which may be seasonal, intermittent, freshwater, brackish, or estuarine, represent a potential point of regulatory interest as they are at risk of heavy metal contamination in the runoff water from the adjacent active ranges. The objective of this project is to demonstrate a relatively low-cost, passive, in situ treatment technology for exclusion of toxic metals in runoff water that can meet the needs of the variable terrain and salinity requirements.

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Small arms firing ranges (SAFRs), situ treatment technology, heavy metal contamination, runoff, variable terrain requirements, reactive filter barrier.

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AOI	Area of Interest
AOS	Apparent Opening Size
B	(fish) Bone, untreated
BB	Boiled (fish) Bone
BBB	Boiled and Bleached (fish) Bone, (3B)
BBBB	Boiled, Bleached and Baked (fish) Bone, (4B)
BMP	Best Management Practice
C&P	Cost & Performance
COTS	Commercial, Off-the-Shelf
DDI S&S	Distilled, Deionized Water Suspend & Settle
DOD	Department of Defense
DP	Demonstration Plan
EL	Environmental Laboratory
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FR	Final Report
FRBerm	Flexible Reactive Berm
ICP-AES	Inductively Coupled Plasma-Atomic Emission Spectrometry
ITRC	Interstate Technology Regulatory Commission
K_d	Partition Coefficient
NPDES	National Pollutant Discharge Elimination System
POA	Percent Open Area
pzc	Point of zero charge
SAFR	Small Arms Firing Range
SM	Site Memorandum
SPLP	Synthetic Precipitate Leaching Procedure
TCLP	Toxicity Characteristic Leaching Procedure
TOC	Total Organic Carbon
TS	Treatability Study
TSS	Total Suspended Solids
USACE	United States Army Corps of Engineers

USEPA	United States Environmental Protection Agency

Metals

Antimony	Sb
Cadmium	Cd
Chromium	Cr
Copper	Cu
Iron	Fe
Lead	Pb
Magnesium	Mg
Manganese	Mn
Nickel	Ni
Uranium	U
Zero-Valent Iron	ZVI
Zinc	Zn

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This report was prepared by Steven L. Larson and W. Andy Martin of the ERDC Environmental Laboratory (EL), Mark Dortch of Los Alamos Technical Associates, J.J. Romano of Alion, Inc., Jeff Sylva of GSI, Inc. and Catherine C. Nestler of Applied Research Associates, Inc. (ARA). The contractor installation and demobilization team consisted of Alion, the Filtrexx advisor, and GSI personnel. . The final report, prepared by Alion, is attached as Appendix C. Robert Kirgan of US AEC oversaw administration of the sub-contract to Alion and GSI. Chemical analysis of the soil and sediment samples was performed by ERDC-EL-Environmental Chemistry.

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EXECUTIVE SUMMARY

This project addressed the contamination of surface waters by munitions residue-contaminated runoff water and sediment from training ranges. Small arms firing ranges (SAFRs) located on Department of Defense (DOD) facilities are, in many cases, constructed next to wetland areas which represent a potential point of regulatory interest as they are at risk from heavy metal contamination in the runoff water from the adjacent active ranges. Access to these areas (especially forested wetlands) is typically limited due to rough terrain and a lack of roads which also makes traditional remediation options and monitoring techniques expensive to implement. Thus, there is a need for a relatively low-cost, passive, in situ treatment technology for exclusion of toxic metals in runoff water.

In a SAFR berm, metals occur in the form of discrete particles (intact munitions or fragments), as well as metal salts (weathering products) and dissolved metal or metallic complexes adsorbed to the soil matrix. When these soils are eroded, the particulate metals that are adsorbed to soils also move with the runoff water (Davis and McCuen 2005). The treatment presented in this report is based on the proven use of a geotextile fabric woven into a tubular shape ("filter sock") and filled with sand. The filter sock is National Pollutant Discharge Elimination System (NPDES)-approved for use on construction sites in order to control transport of sediment in surface water. Metal removal can be enhanced with the addition of innovative amendments to the sand that will adsorb both cationic (such as lead (Pb), zinc (Zn), and copper (Cu)), and anionic (such as antimony (Sb)) metals/metalloids, and metals bound to suspended solids. The chemical amendment investigated was a proprietary commercial mixture of Time Release Amendment Phosphate System™ (TRAPPS™) (Slater UK, Limited). TRAPPS™ is an apatite formulation [$Ca_{10-x}Na_x(PO_4)_{6-x}(CO_3)_x(OH)_2$ with $x < 1$], with relatively insoluble minerals (e.g. phosphate, iron, magnesium and manganese based) tailored to stabilize specific contaminants of concern (i.e. Pb, Sb) (Larson et al., 2007b, Wynter et al. 2012).

The filter sock/amendment concept was proven in the laboratory to successfully remove both TSS-associated metals and dissolved metals (Larson et al. 2016). Dortch (2013) developed a mathematical model to predict the performance and characteristics for the removal of total suspended solids (TSS) of sand filter socks such as the flexible reactive barrier. The model included the effects of TSS clogging the barrier over time. The intended use of the model is for site-specific design of the filters prior to construction and implementation. This model was used to provide design information and predict filter performance for surface runoff water on the field demonstration site. The Kinder Range at Fort Leavenworth, KS, was selected for the field demonstration. Placement of the reactive barriers on the North Kinder Range of Fort Leavenworth, KS was directed by the results of the modeling effort. Barrier placement on the Center Kinder Range was not directed by modeling results.

The objectives of the field demonstration were to:

- Validate application of the reactive filter barrier technology at field scale for removal of heavy metals,
- Validate the sediment transport model developed by ERDC-EL for removal or containment of metal-contaminated sediment in runoff water.

The performance objectives, criteria for evaluation and evaluation are presented in the table below.

Performance Objective	Data Requirements	Success Criteria	Result
Quantitative Performance Objectives			
Reduce concentration of heavy metals (Pb, Cu, Zn, Sb) in runoff water from the SAFR.	Pre- and post-treatment metal concentrations in runoff water	Below Federal and/or State regulatory limits, where established; Pb=15 ppb, Sb=6 ppb, Cu=1.3 ppm, Zn=not established.	Due to lack of funding runoff waters were not sampled
Reduce concentration of total suspended solids (TSS) in runoff water.	Pre- and post-treatment TSS concentrations in runoff water	Turbidity shall not exceed 10 NTU over background turbidity when the background turbidity is 50 NTU or less	Due to lack of funding runoff waters were not sampled
Technology amendments pass TCLP metal regulatory requirements (Pb, Cu, Zn, Sb) for disposal in a non-hazardous waste site.	TCLP of saturated amendments	Technology amendments pass TCLP for metals (Pb, Cu, Zn, Sb), if a regulatory level is available	All socks with the reactive filter barrier passed the TCLP for Pb and for Cu, Zn, and Sn. Sediment that did not pass through the socks did not pass the TCLP for Pb, Cu, Zn or Sn.
Maintain runoff water pH levels	pH measurements of water samples collected on site and in the runoff pathways from the site.	Soil pH = background levels	Due to lack of funding runoff waters were not sampled
Maintain nutrient and TOC concentrations in runoff water at levels to prevent eutrophication of surface water	Pre- and post-treatment nutrient and TOC concentrations in runoff and receiving water	Below Federal and/or State regulatory limits for nutrients and TOC in runoff water; nitrate=10 ppm, TOC=0.05 ppm	Due to lack of funding runoff waters were not sampled
Determine length of use of the amendment technology based on local soils, metal concentrations and precipitation.	Pre- and post-treatment metal concentrations in runoff water to establish breakthrough times, range use, local precipitation amounts	Determine treatment technology replacement time	Runoff waters were not sampled. Longevity assessments were made using the Pb concentration in sediment and reactive barrier material.
Qualitative Performance Objectives			
Ease of use	Feedback from field technicians on time required for treatment placement, frequency of replacement and range downtime	Technology placement requires no or minimal downtime of the range	Success.
Evaluate range management costs	Technology placement method, frequency, and range downtime	LCCA model to develop annual cost to maintain the demonstration range and other ranges	LCCA model was not developed due to lack of funding. Contractor provided long-term technology implementation plan.

Current sediment control technologies include silt fences and straw bales. The advantages of these are their low cost and simple design. However, these designs have shown limited effectiveness for sediment control due to poor installation practices, improper placement and/or inadequate maintenance (US EPA 2012). Training in placement and enhanced installation methods have reduced some of these challenges (US EPA 2012). However, the silt fence/straw bales were never designed to remove heavy metals or other contaminants from the sediment and runoff water.

Current methods for treating heavy metals in runoff water as suggested by the Federal Remediation Technology Roundtable (FRTR) include precipitation and flocculation, treatment with ion exchange resins, and phytoremediation. The costs of these technologies are driven by size and complexity of the site being treated, pre-treatment requirements, and post-treatment/disposal of contaminated treatment waste. They require construction of stormwater detention ponds and treatment facilities through permanent allocation of installation land, a scarce resource.

The advantages of the flexible reactive barrier include:

- It is an engineered control for reducing the velocity of the runoff water and therefore sediment movement
- Removal of heavy metals adsorbed to the sediment
- Adsorption of dissolved metals.
- While more expensive to implement than silt fences/straw bales, it is less expensive than the metal remediation methods such as precipitation/flocculation.
- Flexible reactive barriers do not need use of additional large tracts of land such as required by construction of stormwater detention ponds.
- The reactive barriers are easily installed and removed at end of life.
- The metal adsorption amendment allows the barrier filling material pass the TCLP test for disposal as a non-hazardous waste.

Limitations of the flexible, reactive barrier include:

- Decreased performance under high sediment loading.
- Decreased performance under high velocity water flows.

The cost of installation of the flexible reactive barriers is less than $1,000. Cost will vary depending on the metal-adsorption amendment used. Under appropriate sediment loading conditions, the cost of maintenance over a 30-yr time span will be approximately $5,000, which brings the total cost for treatment of a SAFR to approximately $6,000. Based on ecotoxicity levels for Pb in sediment, the cost avoidance provided by the reactive filter barriers would be $142K for the North Kinder Range and $1,540K for the Center Range.

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1.0 INTRODUCTION

1.1 BACKGROUND

This project addresses the contamination of surface waters by munitions residue-contaminated runoff water and sediment from training ranges. Small arms firing ranges (SAFRs) located on Department of Defense (DOD) facilities are, in many cases, constructed next to wetland areas which represent a potential point of regulatory interest as they are at risk from heavy metal contamination in the runoff water from the adjacent active ranges. Access to these areas (especially forested wetlands) is typically limited due to rough terrain and a lack of roads which also makes traditional remediation options and monitoring techniques expensive to implement. Thus, there is a need for a relatively low-cost, passive, in situ treatment technology for exclusion of toxic metals in runoff water.

In a SAFR berm, metals occur in the form of discrete particles (intact munitions or fragments), as well as metal salts (weathering products) and dissolved metal or metallic complexes adsorbed to the soil matrix. When these soils are eroded, the particulate metals that are adsorbed to soils also move with the runoff water (Davis and McCuen 2005). The treatment presented in this report is based on the proven use of a geotextile fabric woven into a tubular shape ("filter sock") and filled with sand. The filter sock is National Pollutant Discharge Elimination System (NPDES)-approved for use on construction sites in order to control transport of sediment in surface water. Metal removal can be enhanced with the addition of innovative amendments to the sand that will adsorb both cationic (such as lead (Pb), zinc (Zn), and copper (Cu)), and anionic (such as antimony (Sb)) metals/metalloids, and metals bound to suspended solids.

1.1.1 Amendments

The flexible permeable reactive barrier consisted of well-graded sand and one or more amendments that would passively adsorb both dissolved lead and other adsorbed metals and prevent their transport in runoff water and into surface receiving waters or wetlands. The amendments provide for reduction of metal solubility through pH buffering of pore fluids within the barrier, as well as the sequestration of the metals through surface adsorption and the precipitation of insoluble salts (Larson et al. 2005, 2007a, 2007b).

The chemical amendment investigated was a proprietary commercial mixture of Time Release Amendment Phosphate System™ (TRAPPS™) (Slater UK, Limited). TRAPPS™ is an apatite formulation [$Ca_{10-x}Na_x(PO_4)_{6-x}(CO_3)_x(OH)_2$ with $x < 1$], with relatively insoluble minerals (e.g. phosphate, iron, magnesium and manganese based) tailored to stabilize specific contaminants of concern (i.e. Pb, Sb) (Larson et al., 2007b, Wynter et al. 2012). Hydrous oxides of aluminum, iron, magnesium and manganese are ubiquitous in soils and strongly implicated in the sorption of metals and a reduction in metal mobility in soil systems (Bradl 2004, Covelo et al. 2007, Ford et al. 1997, Han et al. 2006, Komárek et al. 2013, Martinez and McBride 1998, Martinez et al. 1999, Ndiba et al. 2008, Orsetti et al. 2006, Trivedi and Ax 2000). The iron hydroxides are generally determined to be more effective at immobilizing Pb and less effective at immobilizing cadmium (Cd) and Cu. However, as the metal oxides aged, the Pb was reported to undergo desorption. Unlike Pb which had rapid initial sorption into ferrihydite, the metals with lower initial sorption (manganese (Mn) and nickel (Ni)) became incorporated into the more stable iron minerals, goethite and hematite, and remained immobilized (Ford et al. 1997, Martinez and McBride 1998).

Copper, Pb, Ni, and Zn have also been reported to adsorb to Mn-oxide. Manganese oxide is a surface acidic oxide with a pH_{pzc} (point of zero charge) of approximately 1.5 to 4.5 (Han et al. 2006). Soil amendment with phosphate reduced the leachability of these complexes by 89% compared to controls (Ndiba et al. 2008).

The other amendment evaluated was a biogenic phosphate derived from waste fishbone. The fishbones are identifiable by their open, mesoporous physical structure (Figure 1).

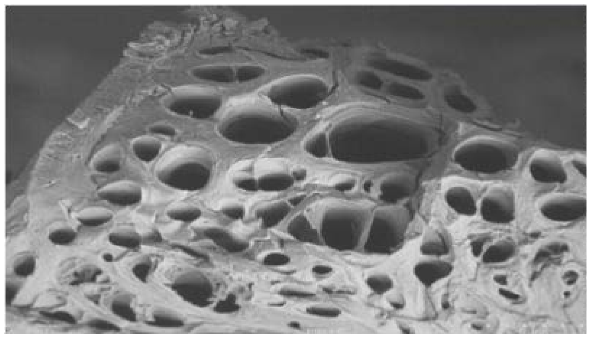

Figure 1. Crushed Salmon Bones (Apatite II™) under High Magnification Showing the Mesoporous Structure

Raw fishbones can be treated to remove organic matter and increase the reactive surface area of the bone. The changes that occur in the physical and chemical characteristics of the biogenic apatite are shown in Figure 2 and Table 1. The treated fishbones are able to adsorb significant concentrations of heavy metals from solution (Larson et al. 2011) (Figure 3).

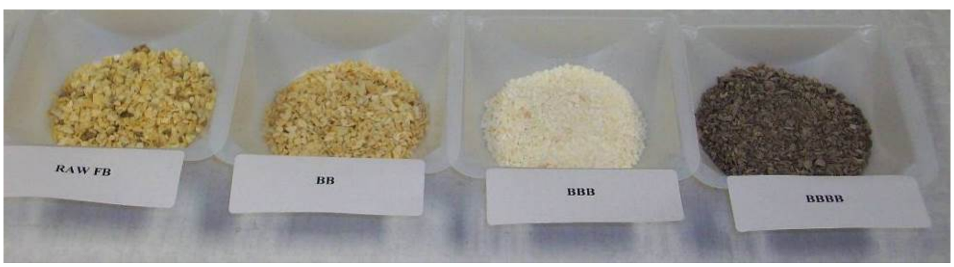

Figure 2. Physical Changes in Fishbone that Occur during Pre-treatment.

Table 1. Chemical Changes in Fishbone that Occur During Pre-treatment.

Parameter measured	Raw FB (B)	Boiled FB (BB)	Boiled and bleached FB (BBB)	Boiled, bleached, and baked FB (BBBB)
Biological oxygen demand (BOD) (mg/g)	>8.36	>8.36	>8.36	0.083
Surface area (m^2/g)	7.4	25.1	92.3	87.4
% with particle size <2.0 mm	0.0	29.4	45.4	80.0
% of initial mass	100	77.5	65.6	44.9

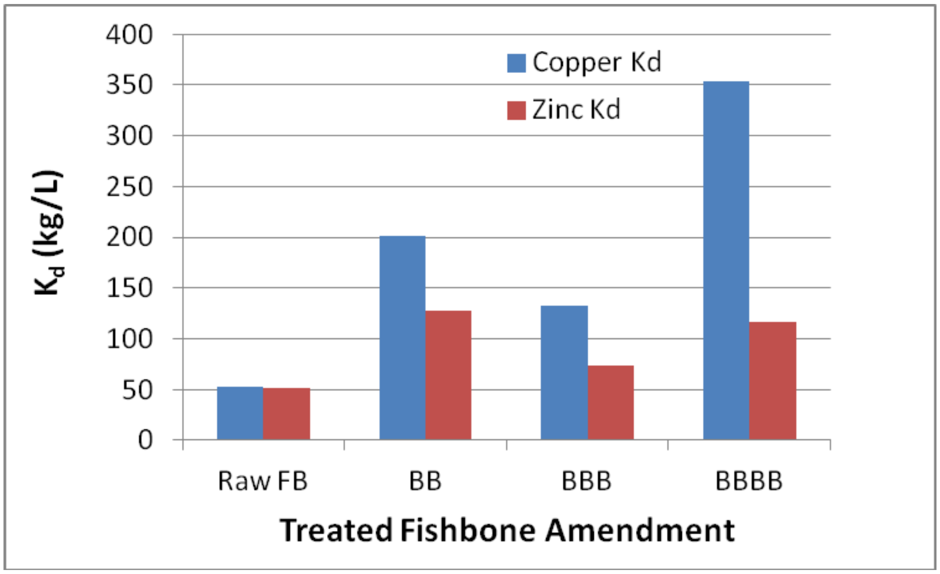

Figure 3. Comparison of K_d Values for Representative Munitions Metals (Copper and Zinc) in Solution with Treated Fishbones.

1.1.2 Sediment Filter Socks

The U.S. Environmental Protection Agency (US EPA) has declared that sediment contamination of our surface waters is the greatest threat to our nation's water resources. Sediment carries particulate-bound metals and other contaminants. Research has shown that the majority of heavy metals leaving small arms ranges is associated with the suspended solids in the runoff water (Tardy et al. 2003). Common best management practices (BMPs) for controlling sediment transport include straw bales, mulch or compost blankets, and silt fences (Faucette et al. 2007). In 2006, the US EPA (US EPA 2006) added compost filter socks as an approved BMP for controlling sediment in runoff water. The use of filter socks resulted in significantly lower turbidity relative to bare soil (Bhattarai et al. 2011, Faucette et al. 2009b). These filter socks are now manufactured by several companies (e.g. Filtrexx International, Layfield Inc., Propex) from different geotextiles and adhere to these US EPA specifications for sediment transport (Faucette et al. 2009a). The different geotextiles have varying porosity, photodegradability, and life expectancy which must be matched to the site requirements and the different amendments. The weight of a filled sock (approximately 40 lbs / linear ft for an 8" diameter, depending on the fill material) effectively prevents sediment migration beneath the sock. The sock is flexible and adheres to varying terrain and slopes (Figure 4).

Figure 4. Photograph of an Erosion Control Filter Sock in Use under Field Conditions.

1.1.3 Proof-of-Concept Study

A preliminary column study examined Pb-contaminated site soil from a southeastern skeet range treated with various concentrations of TRAPPS™, a lead stabilization amendment. A Pb solution of approximately 250-µg Pb/L was added to the columns weekly and the leachate collected and analyzed for heavy metals by inductively coupled plasma-atomic emission spectrometer (ICP-AES). TRAPPS™, available as a commercial, off-the-shelf (COTS) product, is a formulation of apatite and other insoluble minerals, in which Pb is precipitated as stable pyromorphite.

The untreated control had some leachate Pb concentrations that exceeded the state surface water standard. The TRAPPS™ amendment (Formulation 5) at a 25% loading rate maintained the Pb concentration below the state surface water standard which was used as the performance objective for that study.

Following the column study, geotextile filter socks were filled with three types of sand amended with TRAPPS™ #5 and/or processed fishbones at varying concentrations. The filled socks were then used as reactive barriers and studied in mesoscale rainfall lysimeters filled with skeet range soil and watered with the same Pb solution as the column study. Leachate was collected and analyzed for concentrations of soluble and particulate heavy metals by Inductively Coupled Plasma—Atomic Emission Spectrometry (ICP-AES). The results are compared for a reactive filter barrier filled with sand (control) and one with a 15% TRAPPS™ #5 amendment.

The reactive filter barrier using sand amended with 15% TRAPPS™ #5 reduced the concentration of dissolved Pb in the runoff water by 60% or more, relative to the control cells. The concentration of particulate Pb was typically reduced by an order of magnitude.

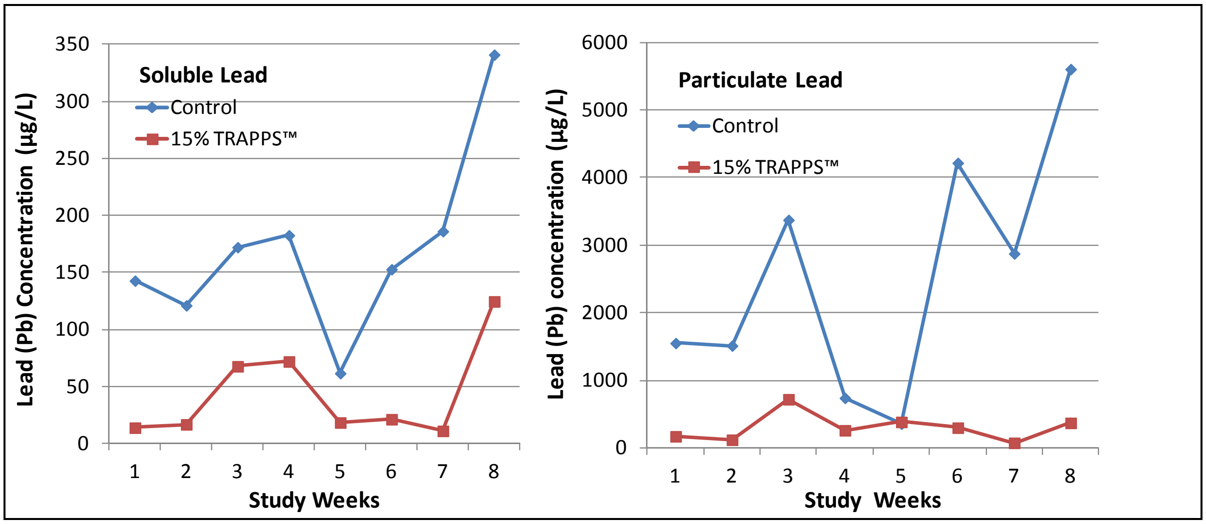

Figure 5. Soluble and Particulate Lead Concentrations (µg/L) in Runoff Water Following Treatment with a Filter Sock Filled with Sand Amended with 15% TRAPPS™.

Given the large watershed areas that need to be protected and the high cost to install and maintain most runoff water management BMPs for metals, the low-cost, easy-to-use filter socks may offer a solution to improving quality of surface receiving waters located adjacent to training ranges. At the end of its use life, the sock filler can be recycled to remove the metals, landfilled, or, potentially, be left in place. The reduction in waste will translate into reduced landfill costs. Combining the filter sock geotextile with amendments for metal immobilization creates a containment system for metals found in surface water runoff from training ranges that is flexible, transportable, inexpensive, and easy to replace.

1.1.4 Model of TSS Removal by Sand Filters

Dortch (2013) developed a mathematical model to predict the performance and TSS removal characteristics of sand filter socks such as the flexible reactive barrier. The model included the effects of TSS clogging the socks over time. The intended use of the model is for site-specific design of the filters prior to construction and implementation. This model was used to provide design information and predict filter performance for surface runoff water on the field demonstration site.

Due to the relatively low flow velocities through the porous media of the sand filters, the model assumes laminar flow through the sock and is, therefore, based on Darcy's law, which states:

$$v = K \frac{H_L}{L_f}$$

where,

v = superficial (Darcy) velocity of flow through the filter, m/hr

K = saturated hydraulic conductivity of the filter, m/hr

H_L = head loss of flow through the filter, m

L_f = thickness or length of flow path of the filter, m

The Darcy velocity is the same as the approach velocity, which is

$$v = \frac{Q}{W_c h}$$

where,

Q = water flow rate through the filter, m^3/hr
W_c = width of the effective drainage approach channel (same as the filter width), m
h = water depth immediately upstream of the filter, m

The primary hydraulic features of sand filter socks are shown in Figure 6, where,

v = superficial (Darcy) velocity of flow through the sock, m/hr
K = saturated hydraulic conductivity of the sock, m/hr
H_f = height, i.e. diameter, of the sock, m
H_L = head loss of flow through the sock, m
L_f = thickness or length of flow path of the sock, m
Q = water flow rate through the sock, m^3/hr, and
H = water depth immediately upstream of the sock.

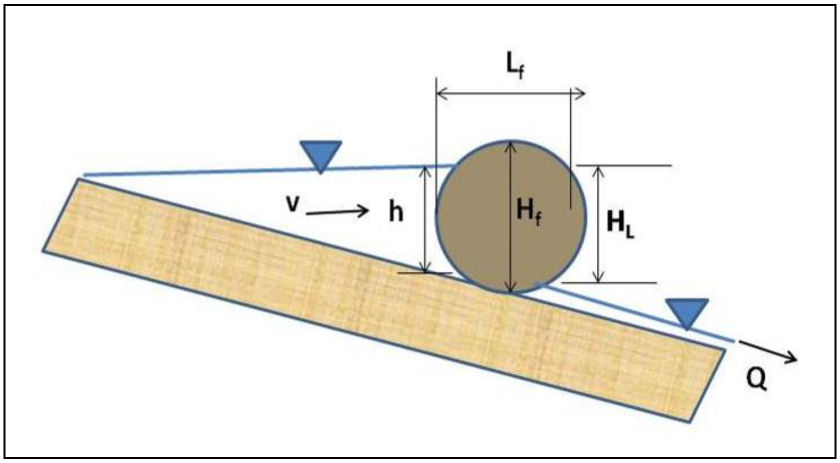

Figure 6. Flow Schematic of the Flexible Reactive Berm.

The model computes the water depth, flow rate, effluent TSS concentration, and filer characteristics (TSS removal coefficient, satuated hydraulic conductivity, and trapped sediment) versus time for a design storm event. The model also estimates effective filter sock life associated with sediment clogging.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objectives of the field demonstration were to:

- Validate application of the reactive filter barrier technology at field scale for removal of heavy metals,
- Validate the sediment transport model developed by ERDC-EL for removal or containment of metal-contaminated sediment in runoff water.

1.3 REGULATORY DRIVERS

The US Environmental Protection Agency (US EPA) has declared that sediment contamination of our surface waters is the greatest threat to our nation's water resources. Sediment also carries particulate-bound metals and other contaminants. Research has shown that the majority of heavy metals leaving small arms ranges is associated with the suspended solids in the runoff water (Tardy et al. 2003). This scenario is directly impacted by the U.S. Clean Water Act (CWA). The CWA establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters. The basis of the CWA was enacted in 1948 and was called the Federal Water Pollution Control Act, but the Act was significantly reorganized and expanded in 1972. Lead in water is regulated under both the CWA and the Safe Drinking Water Act. Individual states and tribes may adopt water quality standards that are more stringent than the Federal regulations but not less protective. The final regulations for lead (and copper) were adopted by EPA in 1991, and later adopted by reference in the Kansas Administrative Regulation 28-15a-80 through 28-15a-91. Actionable levels of lead are 0.015 mg/L (Kansas Department of Health, http://www.kdheks.gov, accessed 11 November 2015).

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2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The proposed technology combines:

- The proven use of geotextile fabric woven into a tubular shape (“sock”) and filled with sand as a means of removing suspended solids from runoff water, with
- The addition of innovative amendments to adsorb cationic [such as lead (Pb), zinc (Zn), and copper (Cu)], anionic [such as antimony (Sb)] metals/metalloids, and metals bound to the suspended solids.

The filter sock is National Pollutant Discharge Elimination System (NPDES)-approved for use on construction sites in order to control transport of sediment in surface water. This project addressed the contamination of surface receiving waters by metal-contaminated runoff water from training ranges by combining sand filler to trap sediment and reactive amendments to bind heavy metals in a proven, flexible berm design.

Several amendments were initially evaluated for use in the sock; phosphate minerals and salts, iron and magnesium oxides, and an innovative combination of mesoscale biogenic phosphate carrier (fishbone apatite) and nanoscale reactive chemicals. The latter combination results in a mesoscale material that is easy to handle and recover while retaining nanoscale reactivity for the stabilization of metals. Bench-scale studies optimized the reactive filler material to iron/magnesium oxides mixed with boiled and bleached fishbones. The oxides were obtained as a COTS product known as “TRAPPS™”. The fishbones were prepared as described in Martin et al. (2008). The nanoscale reactive chemicals tested, such as zero valent iron (ZVI), did not substantially increase the metal adsorption from the runoff water and made the treatment significantly more expensive to implement. This treatment was, therefore, not examined at field-scale.

Application of surface water runoff models designed to decrease sediment transport were used to determine placement of the reactive filter barriers on the ranges (Larson et al. 2016, in press). The models were initially designed to use a single sock barrier and prevent over-topping of that sock. To make the model more realistic for field use, the reactive filter barriers were actually laid in series and overtopping was permitted as the overflow sediment with its load of heavy metal would then be collected by the barriers further downflow in the series. The weight of a filled barrier was approximately 40 lbs / linear ft. for 8” diameter, depending on the fill material. While the barriers themselves were overtopped during heavy rain events, sediment did not migrate beneath them. Given the large land area to be covered, and the high cost to install and maintain most runoff water management BMPs for metals, the low-cost, easy-to-use reactive filter barriers offer a solution to improving quality of surface receiving waters located adjacent to training ranges.

2.2 TECHNOLOGY DEVELOPMENT

Metals are highly associated with the soil particles making up the total suspended solids (TSS) in runoff water (Tardy et al. 2003). Simply removing the sediment from the runoff water by using an erosion control filter sock filled with sand would reduce the concentration of particulate metals transported from the SAFR. However, the sand can also be amended with a reactive material to sorb the dissolved metals in the runoff water. These reactive filter barriers can be assembled and placed in a manner similar to the erosion control socks. Treatability studies were performed at the Hazardous Waste Research Center (HWRC) of the ERDC Environmental Laboratory and are reported in Larson et al. (2016, in press) and detailed in Section 5.0 of this report. Reactive barriers were constructed using a non-woven geotextile filled with well-graded sand amended with 5% (weight: weight, w:w) iron/manganese-oxides (TRAPPS™) and/or 5% (w:w) treated fishbone apatite. The reactive filter barriers were tested under mesoscale lysimeter conditions and metal removal was confirmed. Greater than 95% of the metal in solution was adsorbed by the reactive barrier amendment. Once the reactive material was exhausted it was tested, and found to pass the Toxicity Characteristic Leaching Procedure (TCLP) test for placement in a non-hazardous waste landfill. Positioning of the barriers in the pathway of runoff water for the field demonstration was determined using predictive models for surface runoff. This data and the filter sock model are presented in Larson et al. (2016, in press).

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Two factors influence the amount of lead transported off-site by surface water runoff: the mass of lead fragments left on the range and the velocity of the runoff water. The velocity of the water can successfully be controlled at outdoor ranges by using vegetative, organic, removable and/or permanent ground covers; and by implementing engineered controls which slow down surface water runoff and prevent or minimize the chances of lead migrating off-site (USEPA 2005). Dams and dikes installed perpendicular to the water flow, and ground contouring to divert the flow, are both recommended engineered control devices to slow runoff water. Construction of detention ponds and contaminant traps are other engineered control devices (USEPA 2005).

Current methods for treating heavy metals in runoff water suggested by the Federal Remediation Technology Roundtable (FRTR) include precipitation and flocculation, treatment with ion exchange resins, and phytoremediation (http://www.frtr.gov, accessed 11 November 2015). The costs of these technologies are driven by the size and complexity of the site being treated, pre-treatment requirements, and post-treatment/disposal of contaminated treatment waste. For example, removal of heavy metals by precipitation/flocculation requires collection of the stormwater to be treated, disposal of the contaminated sludge, and a system to return the treated water to the surface water.

The flexible reactive berm combines the advantages of reducing the velocity of the runoff water through engineered controls with heavy metal treatment by removal of particulate metals and adsorption of dissolved metals.

Alternative technologies using the flexible reactive berm approach include using other commercial metal-sorbing amendments. These amendments could be used on their own or mixed with sand in the reactive filter barriers for improved sediment removal. These include MetalLoxx® by Filtrexx.

The disadvantage of the flexible reactive berm is in reducing the very large amount of sediment in the runoff water from an extremely steep slope located behind the firing line of one of the test ranges. In this case, ground contouring for water diversion would be recommended as a first stage engineered control for storm water runoff. This could be followed up by placement of the flexible, reactive berms.

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3.0 PERFORMANCE OBJECTIVES

The performance objectives for the field demonstration of the flexible, reactive berm are presented in Table 2 and detailed in the sections that follow.

Table 2. Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Reduce concentration of heavy metals (Pb, Cu, Zn, Sb) in runoff water from the SAFR.	Pre- and post-treatment metal concentrations in runoff water	Below Federal and/or State regulatory limits, where established; Pb=15 ppb, Sb=6 ppb, Cu=1.3 ppm, Zn=not stated.
Reduce concentration of total suspended solids (TSS) in runoff water.	Pre- and post-treatment TSS concentrations in runoff water	Turbidity shall not exceed 10 NTU over background turbidity when the background turbidity is 50 NTU or less
Technology amendments pass TCLP metal regulatory requirements (Pb, Cu, Zn, Sb) for disposal in a non-hazardous waste site.	TCLP of saturated amendments	Technology amendments pass TCLP for metals (Pb, Cu, Zn, Sb), if a regulatory level is available
Maintain runoff water pH levels at background levels	pH measurements of water samples collected on site and in the runoff pathways from the site	Runoff water pH = background levels
Maintain runoff water pH levels	pH measurements of water samples collected on site and in the runoff pathways from the site.	Soil pH = background levels
Maintain nutrient and TOC concentrations in runoff water at levels to prevent eutrophication of surface water	Pre- and post-treatment nutrient and TOC concentrations in runoff and receiving water	Below Federal and/or State regulatory limits for nutrients and TOC in runoff water; nitrate=10 ppm, TOC=0.05 ppm
Determine length of use of the amendment technology based on local soils, metal concentrations and precipitation.	Pre- and post-treatment metal concentrations in runoff water to establish breakthrough times, range use, local precipitation amounts	Determine treatment technology replacement time
Qualitative Performance Objectives		
Ease of use	Feedback from field technicians on time required for treatment placement, frequency of replacement and range downtime	Technology placement requires no or minimal downtime of the range
Evaluate range management costs	Technology placement method, frequency, and range downtime	LCCA model to develop annual cost to maintain the demonstration range and other ranges

3.1 PERFORMANCE OBJECTIVE: REDUCE CONCENTRATION OF HEAVY METALS (PB, CU, ZN AND SB) IN RUNOFF WATER FROM THE SAFR.

The effectiveness of the technology is a function of the degree to which munitions metals are removed from the range runoff water. Because metals are bound to suspended sediment, success of this demonstration depends on reducing the transport of sediment and the associated heavy metals (Pb, Cu, Zn and Sb) in runoff water through application of the technology. As the socks are filled with sand, to trap suspended sediments, as well as active amendments to adsorb metals, the rate at which the filter becomes silted in can also be used to extrapolate its end time.

3.1.1 Data Requirements

The effectiveness of metal reduction in the runoff water will be evaluated on the basis of metal concentration reductions in runoff water samples taken within the treatment areas. Data required for the remedial effectiveness assessment include pre- and post-treatment metal concentrations in the runoff water. Background and control (untreated) samples for runoff water characterization will be collected and analyzed before the technology implementation.

Demonstration metal concentrations will be compared with background and control concentrations to determine if significant removal has occurred.

3.1.2 Success Criteria

The objective will be considered to be met if the runoff water is below Federal and/or State regulatory limits, whichever is the lowest. A standard student t-test will be used to evaluate the statistical significance of the data. Other statistical tests such as ANOVA or other nonparametric tests may be applied as appropriate to test the significance of the data.

3.2 PERFORMANCE OBJECTIVE: REDUCE CONCENTRATION OF TOTAL SUSPENDED SOLIDS (TSS) IN RUNOFF WATER.

The effectiveness of the technology is a function of the degree to which TSS is removed from the runoff water. Success depends on reducing the transport of sediment and the associated heavy metals (Pb, Cu, Zn and Sb) in runoff water after application of the technology. Data requirements and Success Criteria are similar to those of Section 3.1.

3.3 PERFORMANCE OBJECTIVE: TECHNOLOGY AMENDMENTS PASS TCLP METAL REGULATORY REQUIREMENTS FOR DISPOSAL IN A NON-HAZARDOUS WASTE SITE

The effectiveness of the technology is a function of the degree to which munitions metals are immobilized by the filter sock amendments. Success depends on reducing the transport of sediment and the associated heavy metals (Pb, Cu, Zn and Sb) in runoff water after application of the technology and the TCLP metal concentrations of the saturated amendment. Results of the TCLP analysis will determine whether the spent amendments can be placed in a non-hazardous landfill or re-used on-site (with regulatory approval).

3.3.1 Data Requirements

The effectiveness of metal immobilization by the spent amendments will be evaluated on the basis of metal concentrations in the TCLP analysis of the amendments. Data required for the assessment are post-treatment TCLP metal concentrations from the filter socks.

3.3.2 Success Criteria

The objective will be considered to be met if the TCLP of metals (Pb, Cu, Zn, Sb) in the amendments is below Federal regulatory limits, where established. A standard student t-test will be used to evaluate the statistical significance of the data. Other statistical tests such as ANOVA or other nonparametric tests may be applied as appropriate to test the significance of the data.

3.4 PERFORMANCE OBJECTIVE: MAINTAIN RUNOFF WATER PH LEVELS AT BACKGROUND LEVELS.

A measure of the success of the technology is a function of the degree to which pH of the runoff water is maintained at background levels during treatment.

3.4.1 Data Requirements

The pH of the runoff water will be evaluated from water samples taken within the treatment areas. Background and control (untreated) samples for pH characterization will be collected and analyzed before and during the field demonstration. Demonstration pH values will be compared with background and control levels to determine if any change is significant.

3.4.2 Success Criteria

The objective will be considered to be met if the runoff water pH is within one pH unit of background/control values. A standard student t-test will be used to evaluate the statistical significance of the data. Other statistical tests such as ANOVA or other nonparametric tests may be applied as appropriate to test the significance of the data.

3.5 PERFORMANCE OBJECTIVE: MAINTAIN NUTRIENT AND TOC CONCENTRATIONS IN RUNOFF WATER AT OPTIMAL LEVELS TO PREVENT EUTROPHICATION OF SURFACE WATER.

The effectiveness of the technology is a function of the degree to which nutrients and TOC concentrations in the runoff water are maintained at optimal levels during treatment in order to prevent eutrophication of the surface waters. Data Requirements and Success Criteria are similar to those of Section 3.4.

3.6 PERFORMANCE OBJECTIVE: DETERMINE LENGTH OF USE OF THE AMENDMENT TECHNOLOGY BASED ON LOCAL SOILS, METAL CONCENTRATIONS AND PRECIPITATION.

The effectiveness of the technology is a function of the degree to which munitions metals are removed from the range runoff water. Because metals are bound to suspended sediment, success of this demonstration depends on reducing the transport of sediment and the associated heavy metals (Pb, Cu, Zn and Sb) in runoff water through application of the technology. As the socks are filled with sand, to trap suspended sediments, as well as active amendments to adsorb metals, the rate at which the filter becomes silted in can also be used to extrapolate its end time. This objective is limited to the length of time of the field demonstration. Data Requirements and Success Criteria are similar to those of Section 3.1.

4.0 FORT LEAVENWORTH, KS, KINDER RANGE

4.1 SITE LOCATION AND HISTORY

Fort Leavenworth is the oldest active United States Army post west of Washington, D.C., having been in operation for over 180 years. Fort Leavenworth is located in Leavenworth County, Kansas, immediately north of the city of Leavenworth in the upper northeast portion of the state (Figure 7). It is bordered on the east by the Missouri River and the state of Missouri. The fort currently occupies 5,600 ac and 7,000,000 ft² (700,000 m²) of space in 1,000 buildings and 1,500 quarters. It is located on the Frontier Military Scenic Byway (U.S. Route 69 and K-7 corridor), which was originally a military road connecting to Fort Scott National Historic Site and Fort Gibson.

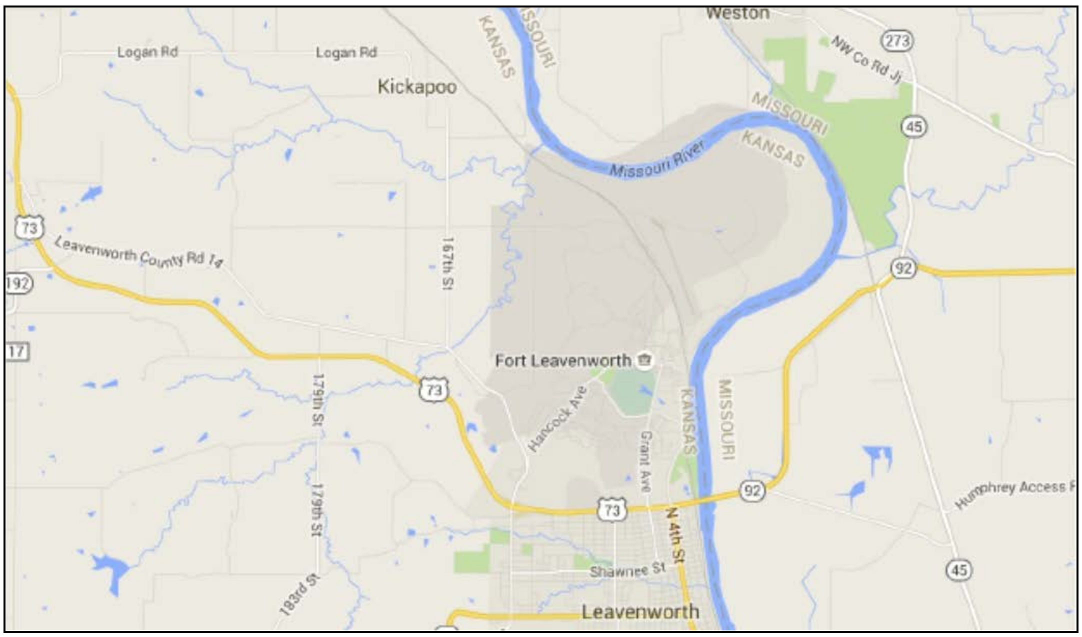

Figure 7. Map Showing the Relationship of Fort Leavenworth, KS to the Missouri River

Fort Leavenworth has been historically known as the "Intellectual Center of the Army" because much of its mission involves training. Major tenants of Ft. Leavenworth include:

- United States Army Combined Arms Center (CAC) which among its various responsibilities is the United States Army Command and General Staff College. It reports to the United States Army Training and Doctrine Command (TRADOC).
- Headquarters of the National Guard's 35th Infantry Division (Mechanized)
- Battle Command Training Center which is the focal point for National Guard of the United States division and brigade staff training and development.

The field demonstration was conducted on the Kinder Range (Figure 8). The firing lines are located adjacent to the road seen in the upper right corner of the photograph. The north range is detailed in Figure 9 and Figure 10. The middle range is shown in Figure 11, Figure 12 and Figure 13.

Figure 8. Fort Leavenworth Kinder Range, North and Middle Small Arms Firing Ranges, Site of the Field Demonstration

Figure 9. The Firing Line and Berms on the North SAFR on Kinder Range, Fort Leavenworth, KS

Figure 10. Satellite View of the North SAFR on Kinder Range, Fort Leavenworth, KS

Figure 11. Satellite View of the Center SAFR on Kinder Range Fort Leavenworth, KS

Figure 12. Details of the Firing Line and Berms on the Center SAFR on Kinder Range, Fort Leavenworth, KS

Figure 13. Close up View of the Bullet Pockets in the Hillside behind the Target Area of the Center Kinder Range, Ft. Leavenworth.

Runoff water has made gulleys lead away from the bullet pockets.

4.2 SITE GEOLOGY/HYDROGEOLOGY

As shown in the figures above, the SAFR berms are the natural earthen slope. Behind this impact berm, there is a wooded area. The trees cover a large, raised plateau with a steep slope down to the range areas. Repeated firing into this slope has resulted in long and deep bullet pockets, which are visible from the treeline toward the firing lines (Figure 13, above). As shown in the figures above, the SAFR berms are the natural earthen slope. Behind this impact berm, there is a wooded area. The trees cover a large, raised plateau with a steep slope down to the range areas. Repeated firing into this slope has resulted in long and deep bullet pockets, which are visible from the treeline toward the firing lines

Precipitation records for Fort Leavenworth, available from the National Climatic Data Center, for the years 2011, 2012, 2013 and 2014 suggest that 2011 was a drought year, during which, there was only 7.46 inches of total precipitation. In contrast, total precipitation during 2012, 2013 and 2014 was 24.51 in, 35.02 in, and 32.83 in, respectively. During the field demonstration, 1 June 2015 to 16 October 2015, there was >15.27 in of rain, with a monthly average of 3.82 in.

The soils of Leavenworth County, KS consist predominantly of silty clay and silty clay loam. Soil from the Kinder Range area has been classified as a gray, Sandy Clay (CL). Soil samples were collected from the top of the berm and from within one of the extended bullet pockets on the range. Soil characterization was performed by the Geotechnical and Structures Laboratory (GSL) of ERDC to determine USACE soil classification and soil particle size distribution. The soil particles size distribution is: 9.9% gravel, 22.6% sand, and 67.5% fines. Of the fines, 38.7% were determined to be silt-sized particles and the other 28.8% consisted of clays.

4.3 CONTAMINANT DISTRIBUTION

Metal contamination is localized to the bullet pockets and the bullet pocket gullies. Larson et al. (2007b) reported a Pb concentration of approximately 9,400 mg/kg in soil fired on in the pilot-scale Live Fire Lysimeter (LFL) by 5,800 bullets. As reviewed in Larson et al. (2007c), older SAFR berms accumulate Pb in the middle berm region (bullet pocket area). Chen et al. (2002) reported Pb concentrations of approximately 17,000 mg/kg in soil that had been in SAFR operation for over a decade.

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5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

This technology combines the proven use of geotextile fabric woven into a tubular shape (a "sock") filled with sand and with the addition of innovative amendments to adsorb both suspended sediments from surface water as well as cationic (such as lead [Pb], zinc [Zn], and copper [Cu]) and anionic (such as antimony [Sb]) metals, metalloids, and metals bound to the suspended solids. The filter sock is National Pollutant Discharge Elimination System (NPDES)-approved for use on construction sites in order to control transport of sediment in surface water.

The sand filter sock performance model (Dortch 2013) was applied to Kinder Range at Fort Leavenworth, KS (Figure 14). The model was used to assess sand filter sock performance for a design storm. Performance measurements consisted of required filter sock diameter and length to avoid water over-topping for the design storm and estimate of filter sock life due to sediment clogging. Other measurements included TSS removal, mass of sediment trapped, and change in the filter sock removal coefficient and saturated hydraulic conductivity for the design storm (Larson et al. 2016, in press).

The model was developed for a sand-only filter sock material, thus, there were accuracy limitations associated with application to the flexible reactive filter barriers featured in this study. The amendments added to sand may affect filter sock characteristics, such as the porosity, average grain size, initial TSS removal coefficient, and sediment clogging coefficients. Also, the flexible reactive barrier system permitted overtopping and filter socks would be arranged in a series in the water flow path. Data collected from the field demonstration study was applied to model refinements.

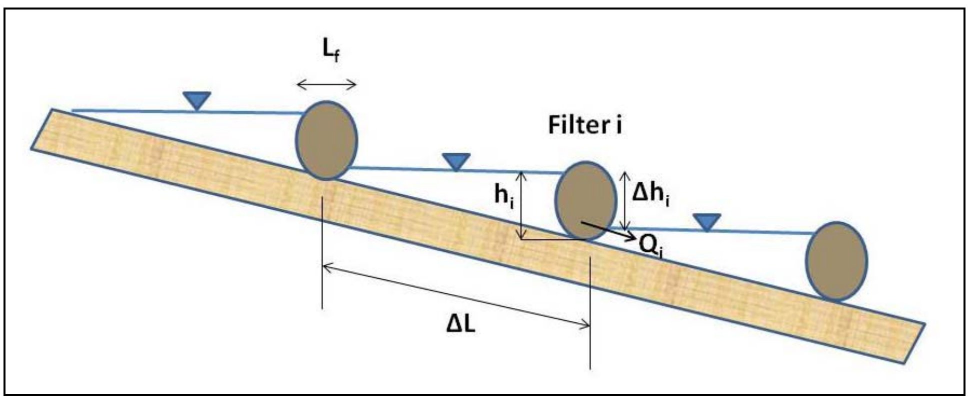

Figure 14. Conceptual Design of the Flexible Permeable Reactive

5.2 BASELINE CHARACTERIZATION

Baseline soil characterization of the Fort Leavenworth Kinder Range is discussed in Section 4.2 of this report.

5.3 TREATABILITY STUDY RESULTS

The results of treatability studies have been presented in Section 2 of this report and detailed in Larson et al. (2016, in press). In summary, as a result of K_d and leach testing evaluation of potential amendments, a combination of sand and TRAPPS™ was selected for the reactive filter barriers. The amendment was added to the sand at a 5% loading rate. The filter barriers were constructed using a commercial geotextile supplied by Filtrexx® International.

5.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The technology components of this study were the reactive filter barrier and a range runoff water model developed by Dr. Mark Dortch and Dr. Billy Johnson (ERDC-EL) through funding leveraged with the EQI 6.2/6.3 Green Range Program (Johnson and Dortch 2014).

The filter barrier technology is made up of a geotextile sock filled with an amended sand mixture. At the Fort Leavenworth demonstration, the sand was amended with 5% TRAPPS™. Two sizes of sand were used; a #60 and a #80. The amendment was mixed and the reactive filter barriers were filled using commercial filter sock assembly equipment such as that shown in Figure 15. In the situation where a commercial mixer isn't available, the sand and amendment can be mixed in a portable cement mixer and the filter socks filled manually. In the event that a commercial metal-sorption amendment is used, the manufacturer may ship pallets of pre-filled reactive barriers to the site.

Figure 15. An Example of Commercial Equipment Used for Filter Sock Assembly

In addition to the reactive filter barriers, Shock Absorbing Concrete (SACON®) blocks were used on the ranges to protect the barriers from stray bullets (Figure 16).

Figure 16. An example of the use of Shock Absorbing Concrete (SACON®) Blocks on a SAFR.

5.4.1 North Range

On the northern range, a 10 foot wide leveling to the right of the actual range was accomplished (Figure 17**,** red rectangle). This leveling was cut to be only a slight downgrade with a length of approximately 30 feet in order to ensure pooling of water for sampling. At the request of the Fort Leavenworth Environmental Division this leveled area was continued after the test location along the length of the range at a greater drop to eliminate water runoff from crossing the range itself.

Figure 17. North Range Showing the Area that was Levelled to Accommodate Placement of the Flexible Reactive Barriers.

A plastic separator was constructed lengthwise to the range in order to separate out the two test filter types (#60 and #80 sand blends) and allow runoff water to flow through both areas (Figure 18). The plastic separator was angled to equalize the water flow.

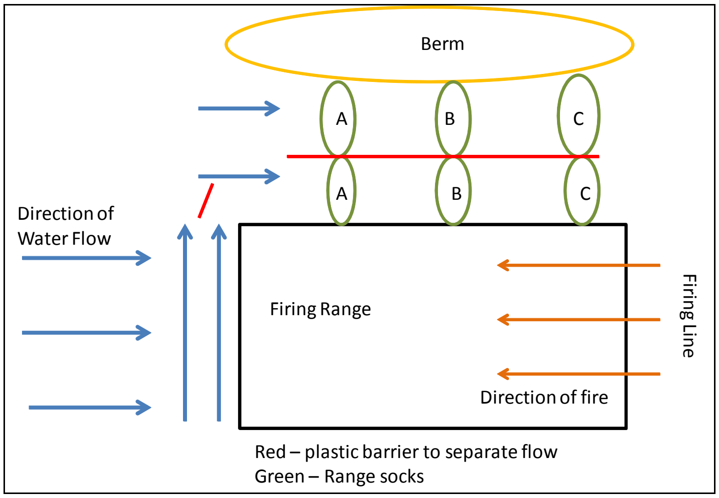

Figure 18. Schematic Showing the Deployment of the Reactive Barriers in Relation to the Firing Line of the Range and the Water Flow Down Range at Fort Leavenworth, KS.

5.4.2 Center Range

Three reactive barriers were placed behind the target ditch. These spanned approximately one third of the entire range culvert. SACON® blocks were placed between these reactive barriers to alleviate filter damage from any inaccurate firing. Three additional filter barriers were placed in the target culvert (trench) in a position to ensure no water enters the culvert drain that is not filtered through the reactive barriers (Figure 19). The assumption was that between the barriers at the edge of the culvert and three inside the trench, all water runoff would be filtered before entering the drain to the culvert that transfers the water outside of the range premises. The reactive filter barrier placement and sampling plan for center range is shown in Figure 20.

Figure 19. Layout of Reactive Filter Barriers on Center Kinder Range, Fort Leavenworth, KS.

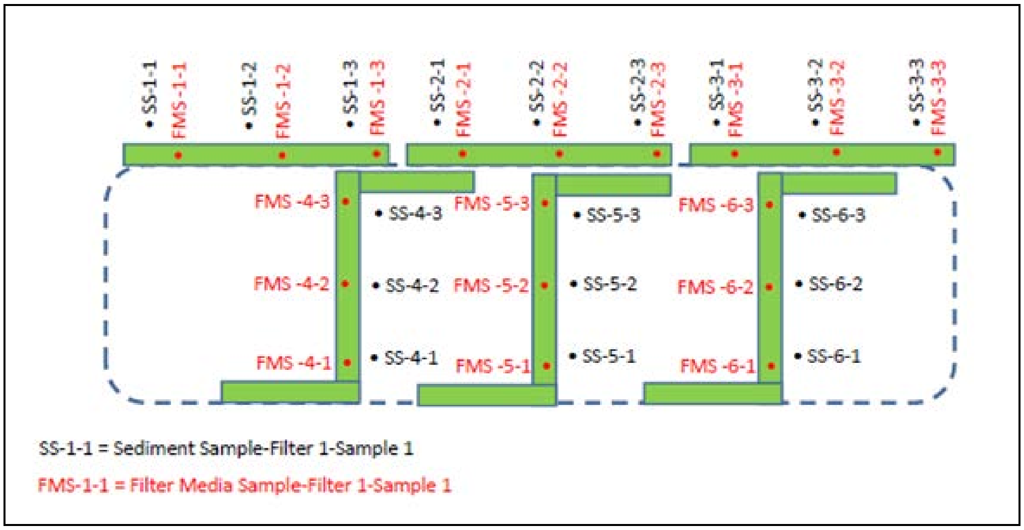

Figure 20. Placement and Sampling Plan of the Reactive Filter Barriers on Center Kinder Range, Fort Leavenworth, KS.

5.5 FIELD TESTING

The Gantt chart (Table 3) shows the schedule for each phase of the field test and how the operational phases were related. The key decision point for this demonstration was the occurrence of rain, both in number of events and in total rainfall. A major rain event occurred two days after system startup and provided immediate feedback on the sturdiness and effectiveness of the flexible reactive berms placed in the flowpath of the runoff water. Following additional rain events in July and August, a date was selected, working with Fort Leavenworth DPW, for system demobilization on 16 October 2016. During the field demonstration, 1 June 2015 to 16 October 2015, there was >15.27 in of rain, with a monthly average of 3.82 in.

Table 3. Gantt Chart for Field Demonstration of the Flexible Reactive Filter Barriers Applied on Kinder Range, Fort Leavenworth, KS.

Task	June	July	Aug	Sept	Oct	Nov	Dec
System startup – completed 2 June 2015							
System operation							
System demobilization – completed 16 October							
Sample analysis							
Reporting							

5.5.1 System start-up

System assembly and start-up was performed by the contractor installation team which consisted of Alion, the Filtrexx advisor and GSI Pacific personnel. ERDC-EL oversight was provided by Dr. W. Andy Martin. The filter sock installation started 1 June 2015 and was completed on 2 June 2015.

The reactive filter barriers were placed first on the North Kinder Range, a small arms firing range. The ground was trenched to allow storm water to flow to the side of the range, preventing flow over the range firing positions. The socks were separated into the #80 sand blend on the left and the #60 sand blend on the right with sturdy plastic separation between the two. Channels were dug from the berm to the north side of the range in an attempt to ensure storm water would flow past and not over the range, and would equally pass through the #60 and #80 sides (Figure 21). The sampling design for this northern Kinder Range is shown in Figure 22.

Figure 21. Post-construction Reactive Filter Barrier Installation on the North Kinder Range at Fort Leavenworth, KS.

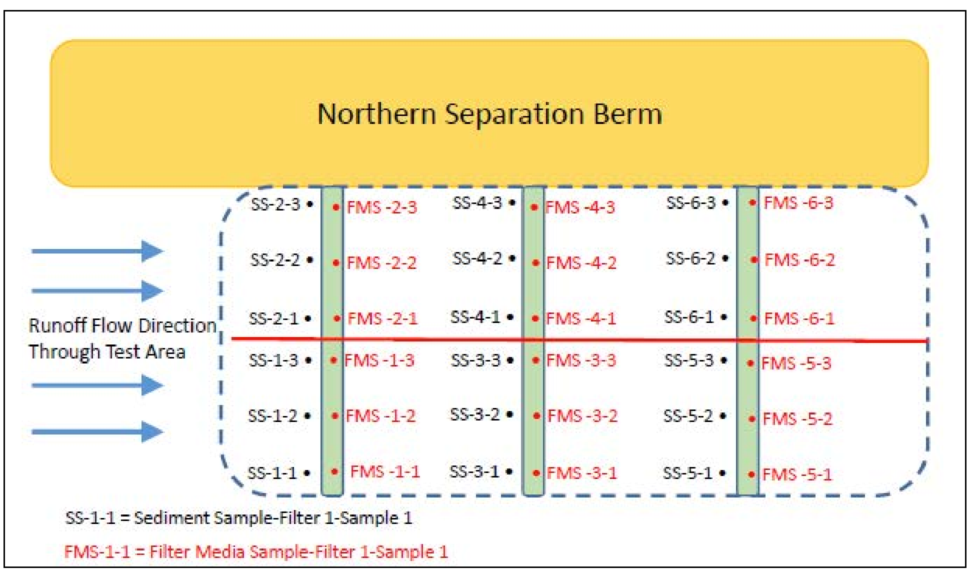

Figure 22. Sampling Layout for the Northern Kinder Range Reactive Filter Barriers.

Additional reactive filter barriers were placed on the Center Kinder Range, both above and in the target trench (Figure 23). SACON® blocks were also placed in front of the reactive barriers immediately behind the targets on the middle range. The sampling plan for the center range is shown in Figure 24.

Figure 23. Post-construction Installation of the Reactive Filter Barriers on Center Kinder Range, Fort Leavenworth, KS.

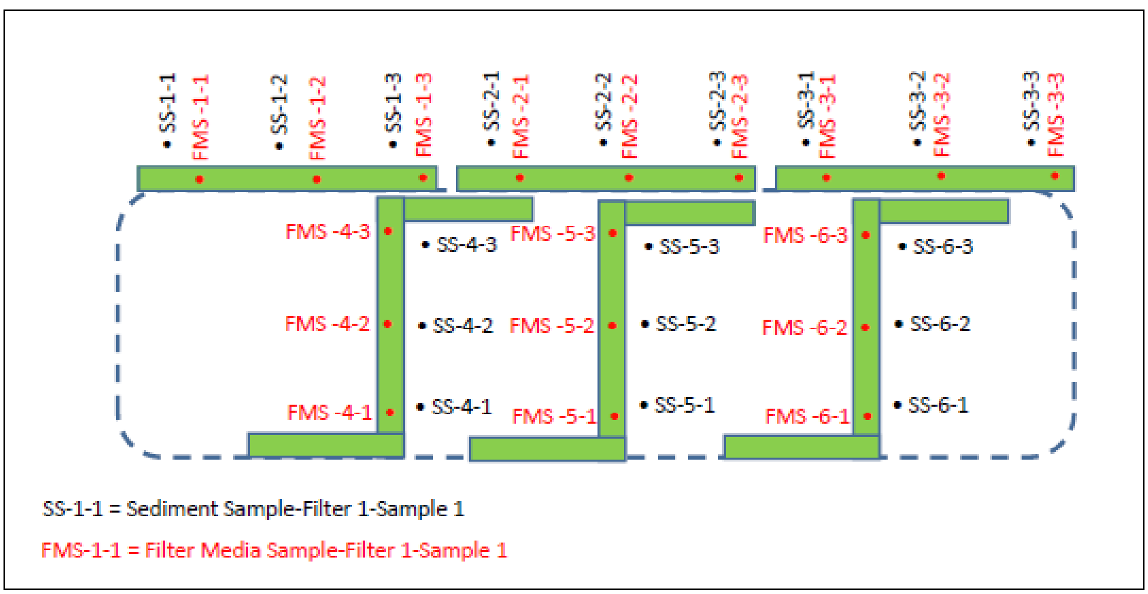

Figure 24. Sampling Layout for the Center Kinder Range Reactive Filter Barriers.

5.5.2 System operation

There was a heavy rain on 4 June 2015, two days after installation (Figure 25). It appeared the trenching did cause the water to flow to the side, and not over, the north range. However, the water did not flow evenly between the #60 and #80 test runs. This was not an issue to the model testing or the reactive filter barrier performance as Pb removal was calculated based on the amount of Pb in the sediment prior to runoff water moving through the first reactive barrier. Several of the filter barriers placed on the North Kinder Range were overtopped by runoff water during some of the heavy rainfall events. Sediment carried over the top of the first barrier in the series was captured by the second and third barriers in the series, as designed.

Figure 25. Reactive Filter Barriers on the North Kinder Range during Heavy Rain on 4 June 2015.

On Center Kinder Range, sediment in the runoff water from the slope was first exposed to the reactive filter barriers at the bottom of the slope (behind the trench). Runoff water and sediment also passed through the reactive filter barriers placed within the trench. One of the filter socks experienced erosion from the force of the runoff water during the storm event (Figure 26).

Figure 26. Performance of the Flexible Reactive Berm Filter Socks during a Heavy Rainstorm 4 June 2015 on the Center Kinder Range.

Left is the "filter wall" slowing runoff water from the berm slope. Overtopping carried sediment and runoff water into the trench. Right (top) is the middle filter barrier placed within the trench behind the firing line. Right (bottom) is a closeup view of a reactive filter opened by the force of the runoff water during the storm event.

5.5.3 System shutdown and demobilization

The appearance of the reactive socks on North Kinder Range at the completion of the study is shown in Figure 27. The contractor reported that the socks on the North Range were placed appropriately and were successful at filtering the runoff water. There was minimal sediment buildup upstream of each reactive barrier.

Figure 27. Appearance of the Reactive Filter Barriers Placed on North Kinder Range at the Completion of the Field Demonstration.

Left: water flow and sediment buildup in front of filter sock 1 (FS1). Right: Close up view of the sandy sediment buildup in front of FS1.

On the Center Kinder Range, the contractor reported a large amount of upstream sediment buildup both behind the trench and within the trench. One sock became completely silted in. The soil after the sock was removed is shown in Figure 28. Some of the SACON blocks sustained bullet damage. However, they functioned correctly to protect the reactive filter barriers.

Figure 28. The Appearance of the Soil Surrounding a Flexible Reactive Filter Barrier on Center Kinder Range after Removal of the "silted-in" Sock.

Both the North and Center ranges of the Kinder Range were sampled before demobilization. Sediment samples were taken upstream of each filter sock and from the socks themselves. The sampling process is detailed in Section 5.6 of this report.

Demobilization after sampling the sediment and reactive barriers consisted of collecting all sediment and socks and placing them in 55-gal drums for removal to ERDC-EL Hazardous Waste Research Center (HWRC) for final analysis. The sites after demobilization are shown in Figure 29. No experimental items were left on-site.

Figure 29. Post Reactive Barrier and Sediment Removal at North Kinder Range (L) and Center Kinder Range (R).

5.6 SAMPLING METHODS

No samples were collected during the period of the actual field demonstration of the flexible reactive berm. This aspect of the proposal was not funded. When the project was complete, but before disassembly of the reactive barriers, samples were collected from the sediment that collected in the front of each barrier as well as from the contents of the barriers themselves (Figure 30). These samples are described in Table 4. Soil and sediment samples were analyzed for heavy metals. In addition, TCLP extraction was performed on the reactive barrier fill material and sediment collected from in front of the barriers. The analysis methods are described in Table 5.

Figure 30. Final Sampling of the Flexible Reactive Filter Barriers on North and Center Kinder Range.

A. Sampling of the filter sock filler material. B. Close up view of the sampling core in the reactive barrier demonstrating the structural integrity of the sock. C. Sampling sediment that settled in front of a reactive barrier on the center Kinder Range.

Table 4. Total Number and Types of Samples Collected from North and Center Kinder Ranges, Fort Leavenworth, KS

Component	Matrix	Number of Samples	Analyte	Location
Pre-demonstration sampling	Soil	Bulk – 5-gal	pH, heavy metals, soil characterization	North and Center Kinder Range
Technology performance sampling	No sampling was performed during the field demonstration.			
Post-demonstration sampling	Reactive barrier fill material	cores	Heavy metals, TCLP	All reactive barriers, North and Center Kinder Ranges
	Sediment	Grab samples	Heavy metals, TCLP	Sediment in front of reactive barriers

Table 5. Analytical Methods for Sample Analysis

Matrix	Analyte	Method	Container	Preservative
Sand and amendment from reactive barrier fill material	Heavy metals-	SW846 Method 3051	Plastic bottle	None
	TCLP	SW846 Method 1311	Plastic bottle	None
Sediment upstream of reactive barriers	Heavy metals-	SW846 Method 3051	Plastic grab bag	None
	TCLP	SW846 Method 1311	Plastic bottle	None

5.7 SAMPLING RESULTS

5.7.1 North Range

5.7.1.1 Metals in North Range Sediment

Triplicate samples were taken from the sediment in front of each of the three reactive barriers on each side of the water flow divider (see Figures 21 and 22, Section 5.5.1). The triplicate samples from each barriers' sediment were combined, dried, homogenized and analyzed for heavy metals. The average concentration of Pb in the reactive barriers is shown in Table 6. The reactive barrier system was designed to be overtopped by heavy rainfall. In this event, the overflow would be captured by the second and/or the third reactive barrier in the series. The success of this plan is seen clearly in the decreasing concentration of sediment Pb in the northern flow path. It is less obvious in the southern flow path, probably due to the larger volume of runoff water and associated sediment treated by this reactive barrier series (anecdotal report from range management).

Table 6. Concentration of Pb (mg/kg) in Sediment Deposited Upstream of Reactive Barriers on North Kinder Range, Fort Leavenworth, KS.

Reactive Barrier Position		Pb concentration (mg/kg)	
		Avg (n=3)	Stdev
North flowpath	1	4,693	2,685
	2	1,887	884
	3	1,210	835
South flowpath	1	6,940	373
	2	6,967	545
	3	4,943	1,417

5.7.1.2 Metals in North Range Reactive Barrier Material

The concentration of Pb extractable from within the reactive barrier filters was observed to be much less than that extracted from the sediment deposited in front of each sock. The average in barriers from the northern flowpath was 50 ± 76 mg/kg, with a range of 4 to 137 mg/kg. The barriers from the southern flowpath contained 86 ± 43 mg/kg, with a range of 37 to 114. The position of the barrier in the flowpath was expected to result in variations in Pb concentration.

Overtopping of the first barrier by runoff water carried water and sediment to the second barrier where it was filtered. Any water that overtopped the second barrier was then treated by the third reactive barrier. The average Pb concentration of the reactive barriers was compared to their associated sediment (Table 7).

Table 7. Comparison of Pb Concentration in Reactive Filter Barriers and their Related Upstream Sediment Deposits, North Kinder Range, Fort Leavenworth, KS

Position		Pb concentration (mg/kg)	
		Avg (n=9)	Stdev
North flowpath	Sediment	2,597	2,175
	Reactive barriers	50	76
South flowpath	Sediment	6,283	1,273
	Reactive barriers	86	43

5.7.1.3 Comparison to treatability studies

The column lysimeter treatability study (Larson et al. 2016, in press) was conducted using Fort Leavenworth soil in order to study the interaction between the sand/amendments, the soil, metals, and TSS. Contaminated soil was sieved and analyzed to establish an initial metals concentration. One-kg of the sieved fines was used to amend the solution added to the column. The input liquid contained 50-µg of Pb per mg of suspended solids. The solution was agitated in order to simulate movement of suspended solids with surface stormwater and allowed to move through the simulated sock under gravity. The initial TSS concentration was 400-mg/L. At one pore volume, this was reduced to 0 mg/L, or non-detectable. At 20 pore volumes, TSS release increased to 50-mg/L. The releases increased with pore volumes until 80 pore volumes had passed through the reactive filter sock material. At this volume, they held steady at 290-mg/L TSS. The Pb output from the column was 20-µg/mg of suspended solids, a 60 percent mass transfer to the amendments over a 10-cn flow length. These values show that the reactive barrier clogged slowly and that there was a close association with the Pb release rate through the first 60 pore volumes of water (Figure 31, Larson et al. 2016, in press).

The results for Pb adsorption by the North Kinder Range reactive filter barriers are not as conclusive as that shown in the laboratory. In part this is due to the finer grain size of the sands that were employed in preparing the barriers. Fine grain sands clog more quickly, leaving sediment in front of the barrier instead of running through the barrier.

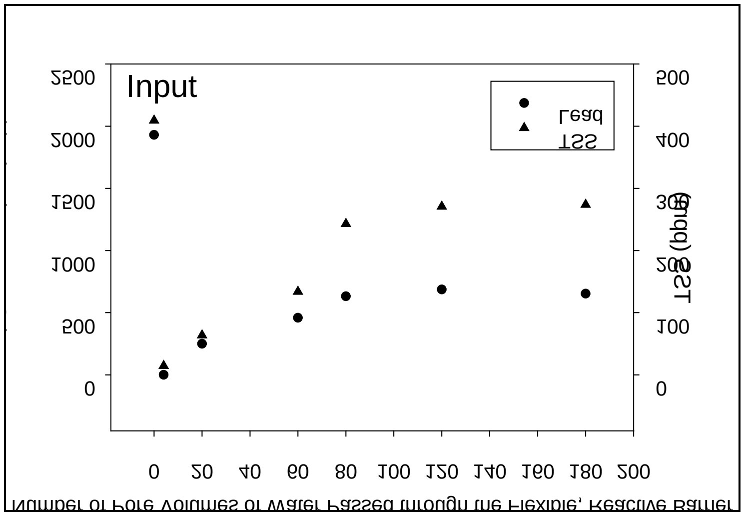

Figure 31. Relationship of Pb Output and TSS Concentration in the Flexible Reactive Barrier (Larson et al. 2016, in press)

A larger scale rainfall lysimeter test was also performed (Larson et al. 2016, in press) which reported that the total mass of Pb leached over 16 rain events was 1.08 x 10^{-2} g. Under these conditions, compared to the concentrations of Pb detected in the leachate, relatively larger amounts of Pb were found in the runoff water; 2.24 x 10^{-2} g.

5.7.1.4 TCLP of North Range Sediment and Reactive Barrier Material

A comparison of the TCLP analysis of the sediment in front of each reactive barrier and within the reactive barriers is shown in Table 8. Each metal for which there is a TCLP regulatory limit is included in this table. Lead was the only metal observed over the TCLP regulatory limit. Lead only exceeded the limit in the untreated sediment from the runoff water. The reactive barriers successfully adsorbed the lead on the TRAPPS™ amendments. At the end of the useful life of the barriers the contents could be reused on-site (with management approval) as berm material or disposed of as non-hazardous waste. This option has the potential to decrease range management costs for the installation.

Table 8. Results of TCLP Analysis of Upstream Sediment and Reactive Barriers from the North Kinder Range, Fort Leavenworth, KS.

Exceedances are shown in red.

Metal	TCLP regulatory limit (mg/L)	Concentration (mg/L)			
		North Range Sediment		North Range Reactive Barriers	
		North flowpath	South flowpath	North flowpath	South flowpath
Arsenic	5	0.02	0.03	0.02	nd
Barium	100	1.75	1.28	0.38	0.35
Cadmium	1	0.02	nd	nd	nd
Chromium	5	nd	nd	nd	nd
Lead	5	48.70	141.33	0.07	0.02
Selenium	1	0.02	0.02	nd	0.03
nd – non-detect					

5.7.2 Center Range

5.7.2.1 Metal Association by Particle Size

The geochemical characteristics of a similar soil to Fort Leavenworth with regard to mineral species present has previously been determined by X-Ray Diffraction (XRD) and Environmental Scanning Electron Microscopy (ESEM) as reported by O'Connor et al. (2007). Tests were conducted both prior to and after firing on the soils with lead bullets. Figure 32 is an ESEM and XRD spectrum for Sandy Clay soil with no lead bullets. The soil has an iron content high enough to be imaged using the backscatter technique. Each metallic particle appears on the image as a white, or near-white, area. The XRD spectrum shows energies characteristic of silicon and aluminum which are integral soil components. Figure 33 illustrates Loess soil after firing with lead bullets. In the area shown, three Pb particles in the size range of 5 to 15 microns can be observed. In the XRD spectrum, peaks representing energies characteristic of Pb are evident. The observed Pb retains its particulate nature and is partially embedded in the soil particle surface (O'Connor et al. 2007).

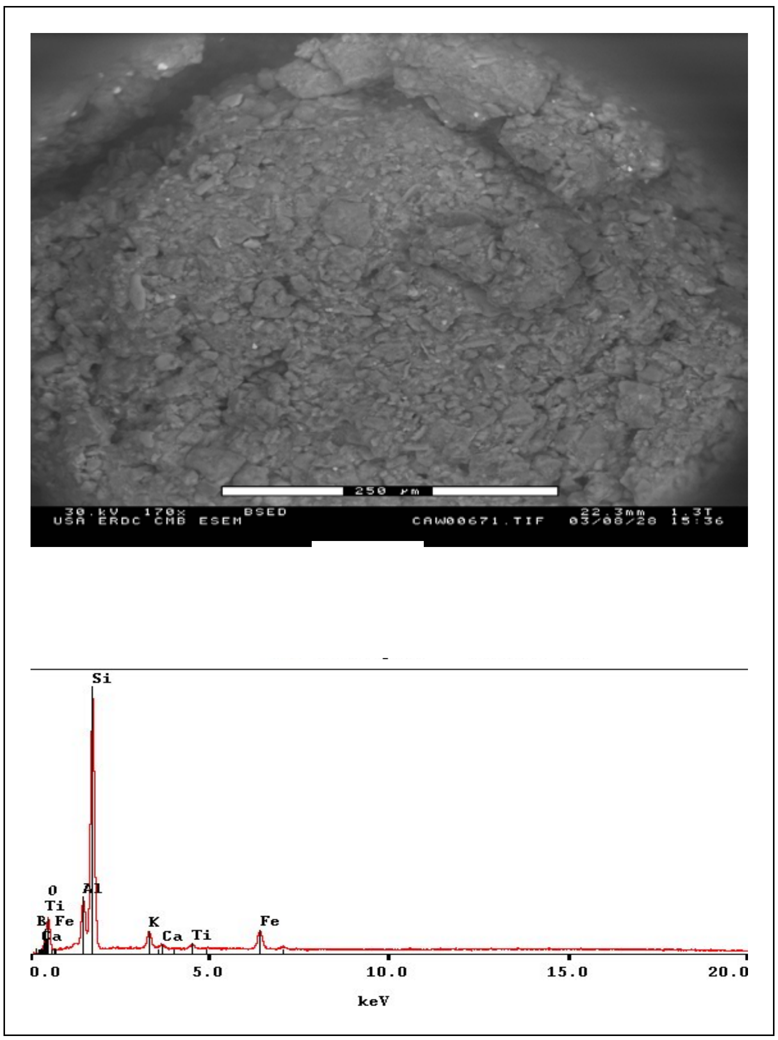

Figure 32. ESEM via BSED and Analysis using XRD of Uncontaminated Sandy Clay Soil.

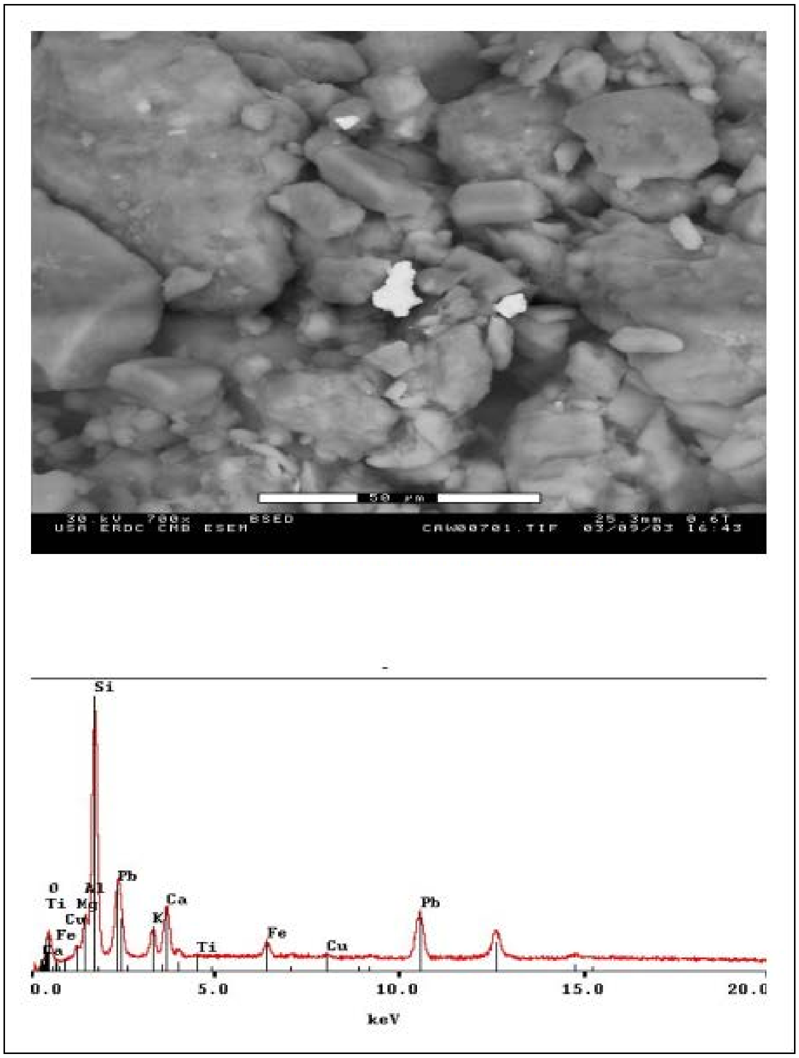

Figure 33. ESEM via BSED and Analysis Using XRD for Loess Soil Fired on with Lead Bullets (O'Connor et al. 2007).

At Fort Leavenworth, Center Kinder Range, triplicate samples were taken from the interior of each of the three filter barriers placed in the trench in the flow path of the runoff water, for a total of nine samples. (For sampling plan see Figure 24, Section 5.5.1). These samples were combined, dried and homogenized. In order to establish whether the lead was preferentially associated with a particular soil particle size, the samples were separated by wet seive using a SWECO Vibro-Energy Round Separator with discreet screen sizes. The particle size fractions analyzed were <200 mm, <135 mm, <50 mm, <35 mm, <20 mm and >20mm. The >20 mm fraction was composed primarily of small rocks. The sieve water was also analyzed for soluble metals.

Figure 34 illustrates the concentration of munitions-associated heavy metals (Sb, Cu, Pb, Ni, and Zn) in the different soil particle size fractions from the amended sand in the reactive filter barrier. No munitions metals were detected in the soluble fraction; all munitions metals were contained in the reactive filter barriers. Copper, Zn and Pb were detected primarily in the <200 mm fraction. However, Pb was also observed in the <35 mm and the <20 mm fractions.

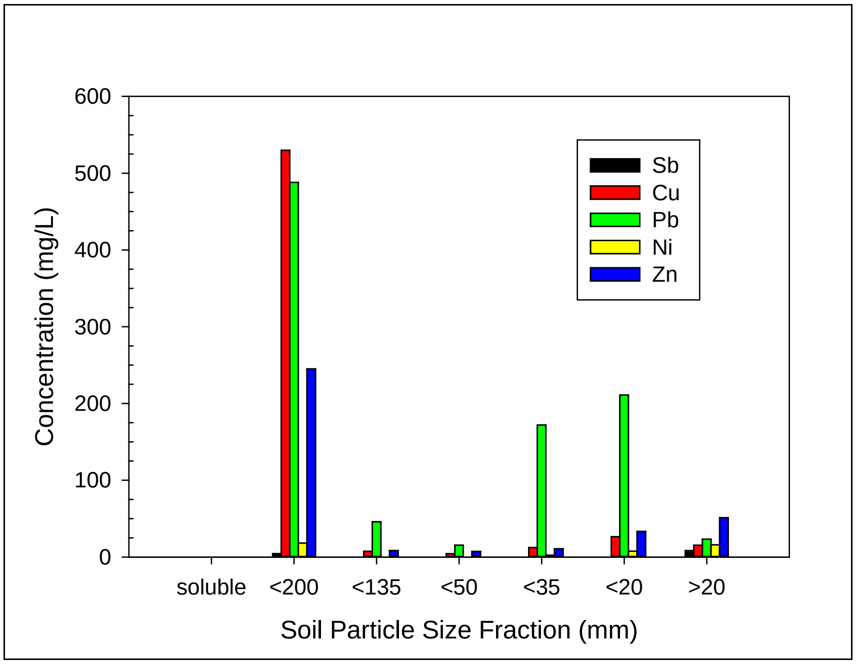

Figure 34. Occurrence and Concentration of Munition-associated Heavy Metals by Soil Particle Size in Sediment from the Center Kinder Range, Fort Leavenworth, KS.

In Figure 35, the Pb concentrations in each soil size fraction are compared to that of iron (Fe) a non-munition metal that is part of the TRAPPS™ amendment formulation. The Pb concentration closely follows the concentration of the amendment, as represented by the Fe. The high Fe concentration in the >20 mm fraction probably reflects the nature of the fraction not the amendment; primarily small rocks.

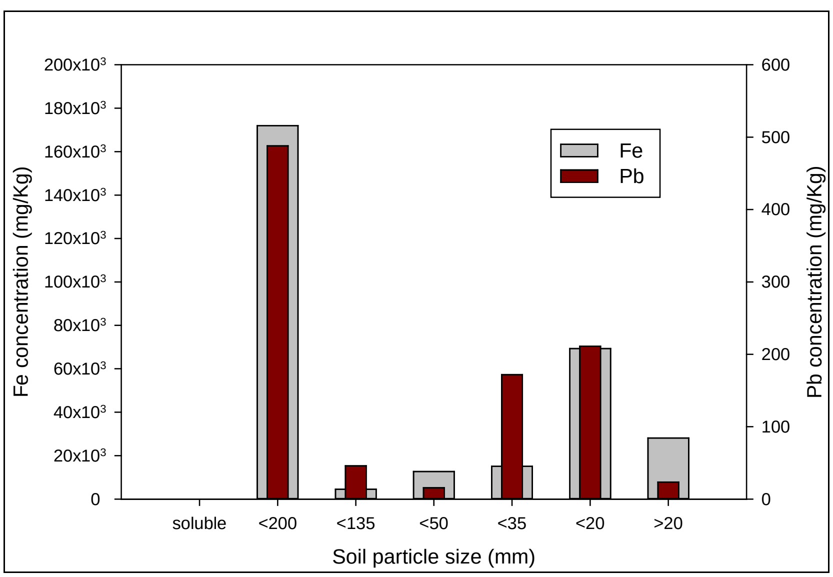

Figure 35. Comparison of lead (Pb) Concentration to that of Iron (Fe), a Component of the TRAPPS™ Formulation, in the Reactive Barrier Filler Material Used on the Center Kinder Range.

5.7.2.2 Metals in Center Range Sediment

Triplicate samples were taken from sediment that built up in front of each of three reactive barriers behind the trench at the bottom of the hill berm. Samples were also taken from in front of each reactive barrier inside the firing line trench (see Figure 24, Section 5.5.1). The in-trench reactive barriers received water that overtopped the hill barriers along the entire length of the trench. The triplicate samples from each reactive barrier were combined, dried, homogenized and analyzed for heavy metals. The sediment from the reactive barriers on the hill contained an average of 4,373 ± 1,635 mg/kg of Pb. The sediment from the reactive barriers located in the trench contained an average of 7,560 ± 2,469 mg/kg of Pb. Results of a student t-test performed on the data indicate that there is not a statistically significant difference between the two sets of data (p=0.136). This result is probably due to the heavy overtopping that was observed during most rain events (anecdotal from contractor's report). Sediment containing Pb was carried by the untreated storm runoff water into the entire length of the trench. Therefore, each reactive barrier in the trench functioned more as a primary treatment instead of secondary or tertiary treatment.

5.7.2.3 Metals in Center Range Reactive Barrier Filler Material

The concentration of Pb extractable from within the reactive barrier filters was observed to be much less than that extracted from the sediment deposited in front of each reactive filter barrier. The average in barriers from the flowpath directly off the hill berm was 50 ± 76 mg/kg, with a range of 4 to 137 mg/kg. The barriers in the trench flowpath contained 86 ± 43 mg/kg, with a range of 37 to 114. The position of the barrier in the flowpath was expected to result in variations in Pb concentration. However, as discussed above, heavy overtopping observed during most rain events carried water and sediment to the in-trench barriers where they functioned more as a primary treatment instead of secondary or tertiary treatment. The average Pb concentration of the reactive barriers was compared to their associated sediment (Table 9).

Table 9. Comparison of Pb Concentration (mg/kg) in Reactive Filter Barriers and their Related Upstream Sediment Deposits, Center Kinder Range, Fort Leavenworth, KS

Position		Pb concentration (mg/kg)	
		Avg (n=9)	Stdev
Hill berm behind target trench	Sediment	4,373.33	1,635.37
	Reactive barriers	180.47	118.81
In trench	Sediment	7,560.00	2,469.39
	Reactive barriers	168.87	150.34

5.7.2.4 TCLP of Center Range Sediment and Reactive Barrier Filter Material

A comparison of the TCLP analysis of the sediment in front of each reactive barrier and within the reactive barriers is shown in Table 10. Each metal for which there is a TCLP regulatory limit is included in this table. Lead was the only metal observed over the TCLP regulatory limit. Lead only exceeded the limit in the untreated sediment from the runoff water.

The reactive barriers successfully adsorbed the Pb on the TRAPPS™ amendments. At the end of the useful life of the barriers the contents could be reused on-site (with management approval) as berm material or disposed of as non-hazardous waste. This option has the potential to decrease range management costs for the installation.

Table 10. Results of TCLP Analysis of Upstream Sediment and Reactive Barriers from the Center Kinder Range, Fort Leavenworth, KS.

Exceedances are shown in red.

Metal	TCLP regulatory limit (mg/L)	Concentration (mg/L)			
		Center Range Sediment		Center Range Reactive Barriers	
		Hill	Trench	Hill	Trench
Arsenic	5	0.03	0.04	nd	nd
Barium	100	2.12	1.60	0.36	0.38
Cadmium	1	nd	nd	nd	nd
Chromium	5	nd	nd	nd	nd
Lead	5	145.00	136.00	1.52	4.21
Selenium	1	0.03	0.03	0.02	0.03
nd – non-detect					

6.0 PERFORMANCE ASSESSMENT

A performance assessment of the reactive barrier technology as demonstrated on the North Kinder Range, Fort Leavenworth KS is provided in Table 11.

Table 11. Performance Assessment of the Reactive Filter Barrier as Demonstrated on North Kinder Range, Fort Leavenworth KS

Performance Objective	Data Requirements	Success Criteria	Result
Quantitative Performance Objectives			
Reduce concentration of heavy metals (Pb, Cu, Zn, Sb) in runoff water from the SAFR.	Pre- and post-treatment metal concentrations in runoff water	Below Federal and/or State regulatory limits, where established; Pb=15 ppb, Sb=6 ppb, Cu=1.3 ppm, Zn=not established.	Due to lack of funding runoff waters were not sampled
Reduce concentration of total suspended solids (TSS) in runoff water.	Pre- and post-treatment TSS concentrations in runoff water	Turbidity shall not exceed 10 NTU over background turbidity when the background turbidity is 50 NTU or less	Due to lack of funding runoff waters were not sampled
Technology amendments pass TCLP metal regulatory requirements (Pb, Cu, Zn, Sb) for disposal in a non-hazardous waste site.	TCLP of saturated amendments	Technology amendments pass TCLP for metals (Pb, Cu, Zn, Sb), if a regulatory level is available	All socks with the reactive filter barrier passed the TCLP for Pb and for Cu, Zn, and Sn. Sediment that did not pass through the socks did not pass the TCLP for Pb, Cu, Zn or Sn.
Maintain runoff water pH levels	pH measurements of water samples collected on site and in the runoff pathways from the site.	Soil pH = background levels	Due to lack of funding runoff waters were not sampled
Maintain nutrient and TOC concentrations in runoff water at levels to prevent eutrophication of surface water	Pre- and post-treatment nutrient and TOC concentrations in runoff and receiving water	Below Federal and/or State regulatory limits for nutrients and TOC in runoff water; nitrate=10 ppm, TOC=0.05 ppm	Due to lack of funding runoff waters were not sampled
Determine length of use of the amendment technology based on local soils, metal concentrations and precipitation.	Pre- and post-treatment metal concentrations in runoff water to establish breakthrough times, range use, local precipitation amounts	Determine treatment technology replacement time	Runoff waters were not sampled. Longevity assessments were made using the Pb concentration in sediment and reactive barrier material.
Qualitative Performance Objectives			
Ease of use	Feedback from field technicians on time required for treatment placement, frequency of replacement and range downtime	Technology placement requires no or minimal downtime of the range	Success.
Evaluate range management costs	Technology placement method, frequency, and range downtime	LCCA model to develop annual cost to maintain the demonstration range and other ranges	LCCA model was not developed due to lack of funding. Contractor provided long-term technology implementation plan.

The modeling that was conducted prior to the field demonstration assumed a filter medium of course sand with a median grain size on the order of 1 mm. This was based on the results of the treatability study (Larson et al. 2016). At the demonstration site, two fine grain sands had been purchased therefore they were used in the filter socks for the demonstration. The model showed that the larger sand grain size was required to prevent severe over-topping for the design storm. Finer grain size causes less water to flow through the filter with more water ponding before eventual over-topping. When water flows more easily through the filter, there is greater tendency for TSS to be trapped within the filter rather than settling out of the ponded water column upstream of the sock. By moving through the filter, the metals are adsorbed onto the reactive amendment. The sampling results shown in Table 7 indicate that far more lead (and the TSS onto which lead is adsorbed) was settled upstream of the filters than trapped within the filters. It is believed that the use of coarser sand within the filters would have resulted in more lead being trapped within the filters and less lead settled upstream of them.

7.0 COST ASSESSMENT

7.1 COST SUMMARY

A simple cost summary of the flexible, reactive berm (FRBerm) technology is provided in Table 12. The major cost elements include the geotextile and the reactive filler material for each sock. These are site specific costs. Costs are given per linear foot of reactive barrier. Labor to install the reactive socks was not a significant cost, but is noted in Table 12. Waste disposal of contaminated reactive socks and sediment accrued by the field demonstration was handled by the EL-HWRC. Disposal costs to the installation on implementation of this technology was estimated by the field installation contractor and is included in Table 12. As the filler material passed the TCLP test, it could be sent to a non-hazardous waste landfill or reused on-site in, for example, berm construction.

Table 12. Cost Model for the Reactive Barrier Filters.

Cost Element	Data Tracked During the Demonstration	Costs	
Treatability study	• Personnel required and associated labor • Materials • Analytical laboratory costs	Lab technician, 80 h Project engineer, 80 h	$32,000 $67,300
		Materials	$23,500
		Analytical laboratory	$5,400
Baseline characterization	• Detailed hydraulic assessment required, costs associated with labor and materials tracked	Field technician, 40 h Project engineer, 15 h	$15,000 $36,700
		Materials	$10,000
Total non-recurring initial costs			**189,900**
Material cost	Unit: $ per foot of reactive barrier Data requirements: • Initial amount of material required based on recommended width and depth of reactive sock • Reapplication rate as stated in surface water model and life cycle analysis	• COTS product costs range from $3.33 to $14.58 per foot of pre-filled reactive filter barrier. Cost varies depending on the type of amendment. • Shipping costs are $2.08 per foot of reactive barrier. • Re-application frequency is detailed in Table 12.	
Installation	Unit: $ per year Data requirements: • Recommended installation method • Mobilization cost • Time required	• Labor $1,000 per year for 2 ranges installation/removal of reactive barriers. • Installation required one, eight hour day for three workers and included site preparation (grading) where deemed necessary by installation DPW. • COTS reactive barriers are delivered with the approved installation stakes, which are included in the cost and shipping charges.	
Waste disposal	• Hazardous waste sediment disposal	$10,000/year, contractor estimate for Pb-contaminated sediment	
Operation and maintenance costs	• No unique requirements	NA	
Long-term monitoring	• Not required	NA	

7.2 COST DRIVERS

The cost drivers for implementation of this technology are the concentration of sediment carried by the surface water runoff and the annual volume of storm runoff water. Runoff water with high sediment concentrations will require more frequent change-outs of the foremost reactive barrier as the barrier will clog more rapidly. This will increase the cost of maintaining the technology. In drought years, the life of the barriers would be extended. In rainy years, or tropical climates with high rainfall, and high sediment transport, the lifetime of the barrier could be reduced.

7.3 COST COMPARISON

The cost comparison is based on a site the size of a small to medium firing range with soil berm in a temperate region with moderate rainfall. The North Kinder Range has an approximate catchment area of 2,500 m^2, or about 0.6 acres. The ERDC-EL sediment model uses an average annual maximum 24-hour storm, which has a rainfall of about 2.85 inches (USDC 1961). Full parameters are described in Larson et al. (2016).

One of the current methods for simply containing the sediment in runoff water is a silt fence. These are temporary devices, used primarily on construction sites. The fence is porous fabric held up by wooden or metal stakes (Figure 36). The silt fence is designed to protect quality of nearby receiving waters from sediment carried by stormwater runoff. Runoff water moves through the fence material. A single 100-foot run of fence can hold back 50 tons of sediment. The advantages of silt fences are their low cost and simple design. However, they have shown limited effectiveness for sediment control due to poor installation practices, improper placement and/or inadequate maintenance (US EPA 2012). Training in their placement and enhanced installation methods have reduced some of these challenges (US EPA 2012). However, the silt fence was never designed to remove heavy metals or other contaminants from the sediment and runoff water.

Figure 36. Example of the Use of a Silt Fence as a Best Management Practice for Sediment Control in Runoff Water from a Construction Site.

Current methods for treating heavy metals in runoff water, as suggested by the Federal Remediation Technology Roundtable (FRTR), include precipitation and flocculation, treatment with ion exchange resins, and phytoremediation (http://www.frtr.gov, accessed 11 November 2015). The costs of these technologies are driven by size and complexity of the site being treated, pre-treatment requirements, and post-treatment/disposal of contaminated treatment waste. For example, removal of heavy metals by precipitation/flocculation requires collection of the stormwater to be treated, disposal of the contaminated sludge, and a system to return the treated water to the surface water. The precipitation/flocculation treatment is reported to cost from $19.99 to $48.20 per 1,000 gallons of water treated ($2015). This cost includes design and contingency calculations. This cost doesn't include either the pre- or the post-treatment. For example, sludge disposal could add an additional $0.50 per 1,000 gallons. This cost also doesn't include the construction of a concrete retention pond to collect the runoff water ($205,300 $2015). Ion exchange requires pre-treatment to remove suspended solids from the water being treated and would best be employed as part of a treatment train. The regenerant would also need disposal.

Phytoremediation would require design and construction of a shallow wetland. Metals are removed from the collected sediment and water through ion exchange, adsorption, absorption, and precipitation with geochemical and microbial oxidation and reduction. Seasonal conditions may limit the effective treatment time and, like the other treatments described above, it requires a large area of land committed to this purpose. ITRC (2005) notes that project management and engineering for wetlands construction projects can run as high as 10% to 20% of the total budget. Other costs, outside the straightforward purchase of land and plants, include permitting, and post-construction monitoring and maintenance. These non-construction costs can run as high as another 25% of the total project cost.

The flexible reactive berm was designed to be a low-cost alternative technology between simple sediment removal devices and complicated and expensive metal treatment technologies. The reactive barrier:

- retains the flexibility and sediment removing function of the silt fence,
- adds the ability to remove metals directly from runoff water and sediment fines.

The reactive barrier technology quantifies cost by linear foot of barrier instead of gallons of water treated. The model specifies the quantity of barrier required based on the historical average rainfall amounts, historical maximum storm events and the soil type of the area. There are also alternative amendments for use in the reactive berm that are available commercially, including MetalLoxx® by Filtrexx.

Costs of installation and maintenance of the flexible, reactive barriers for the North and Center Kinder Ranges over a 30-yr operational life span are shown in Table 13. Although a direct comparison to water treatment costs aren't possible, the 30-yr total cost of the reactive barriers is much less than a stormwater detention pond plus flocculation, ion exchange, and hazardous waste disposal of contaminated sediment.

Table 13. Cost per Linear Foot for Removing Metals from Runoff Water ($2015) Using Reactive Filter Barriers for a 30-yr Operational Timeframe.

Item	Cost	North Kinder Range	Center Kinder Range
Linear feet required for initial installation		20	180
Cost per foot of pre-filled reactive barrier (cost range depends on selected amendment)	$3.33 to 14.58	$67 - $292	$599 – $2,624
Shipping per foot	$2.08	$42	$374
Total material cost		$109 - $334	$973 - $2,998
Labor for installation	$1,000 for 2 ranges	$500	$500
Total for initial installation		**$609 - $834**	**$1,473 – $3,498**
Number of overhauls		1 per 4 years, (10 ft)	2 per year, (120 ft)
Cost for maintenance (filter barrier + shipping + labor))		$554 to $667	$1,150 to $2,500
Number of overhauls in 30 yr		7.5	30
Total cost of overhauls for 30 yr		**$4,155 to $5,003**	**$34,500 to $75,000**
30 yr Total Cost (Initial + Overhaul)		**$4,764 to $5,837**	**$35,973 to $77,500**

7.4 COST AVOIDANCE

A large amount of contaminated sediment was removed from the Kinder Range runoff water from both the North and Center Ranges (Table 14). Cost avoidance calculations used the volume of sediment and the concentration of Pb in the sediment compared to the cost of remediation of that sediment. The Lowest Effect Level (LEL) for Pb in sediment has been set at 31 mg/kg. This is the concentration at sediments are considered marginally polluted. Ecotoxic effects become apparent in these sediments but the majority of sediment-dwelling organisms are unaffected. In contrast, The Severe Effect Level (SEL), set at 250 mg/kg Pb, is the point at which the health of sediment-dwelling organisms is affected.

Table 14. Cost avoidance of the flexible reactive filter barriers based on ecotoxic screening levels of Pb in sediment.

Range	Average [Pb] (mg/kg)	Sediment volume (yd^3)	Total sediment volume at SEL	Remediation cost[1] ($K)	Total sediment volume at LEL	Remediation cost[1] ($K)
North	4,400	2	35	17.6	284	142
Center	5,967	16	282	190.9	3,080	1,540
[1]Remediation cost estimated at $500/yd^3						

8.0 IMPLEMENTATION ISSUES

The prototype filter, using coarse sand and a COTS amendment was successful at removing metals in solution and sorbed to fine sediment. The testing also provided valuable information that was incorporated into the runoff water model developed by ERDC-EL. Even though the field demonstration did not follow exactly the requirements as set out by the laboratory studies and the runoff water model, the demonstration proved the usefulness of the reactive filter barriers.

Maintenance solutions were developed for the Fort Leavenworth North and Center Kinder Ranges. These proposed solutions highlight implementation issues associated with the reactive filter barriers.

North Range: Implementation issues were minimal on the north range. The relatively level ground to the north (right) side of the range provided gentle water flow without major sediment buildup. The small amount of sediment in the runoff water was contained completely by the sock filters.

The contractor-recommended long-term maintenance solution is to place two, 10 foot long reactive filter barriers three feet apart in the back of this area (Figure 38). With the small amount of sediment flowing in this area, these socks would last up to four years before replacement was needed. The majority of the sediment-bound metals and metal(loids) would be removed from the storm water at this point. Planning should include removal and replacement of the leading filter on the slope at least every four years and the second filter every eight years. With no sediment flow to cause issues, the storm water could be filtered again on the north side drainage area using two reactive filter barriers to adsorb any remaining heavy metals and metal(loid)s in solution.

The reactive barriers are contaminated with heavy metals. A TCLP test would determine whether hazardous or non-hazardous waste disposal would be required. Any sediment collected upstream of the barriers would require hazardous waste disposal.

Figure 37. Schematic of the Proposed Implementation of Flexible Reactive Filter Barriers on North Kinder Range.

Center Range: The center range had significant metal-contaminated sediment in the runoff water. A temporary maintenance solution would be to use approximately 60 feet of reactive barrier in a line approximately 9 to 12 feet back from the rear of the target trough, with an additional 60 feet approximately six feet behind the first. Another 60 feet of reactive filter barrier should be placed immediately behind the cement target trough (Figure 39). While these reactive barriers could be placed at the current ground level, it would be more effective, although more expensive, to level the ground behind the target trough so that the bottom of the final reactive filter sock would be slightly below the lip of the trough. Also, the ground sloping upwards to the hill berm could be leveled, or even made into a slight depression, so the runoff water would have less chance of spill over away from the range.

For maintenance of the center range, the layer closest to the hill berm (Sock 1) would be replaced every year. Sock 2 would be replaced every other year. Sock 3 would be replaced every third year (Table 14). If a longer term solution is implemented, with a reduction in storm water flow down the hill, the lifetime of the filters would be greatly extended. As with the North Kinder Range, if the filter barriers pass the TCLP, there may be the option of non-hazardous waste disposal and/or re-use on-site. The sediment contained upstream of each barrier must be disposed of as hazardous waste.

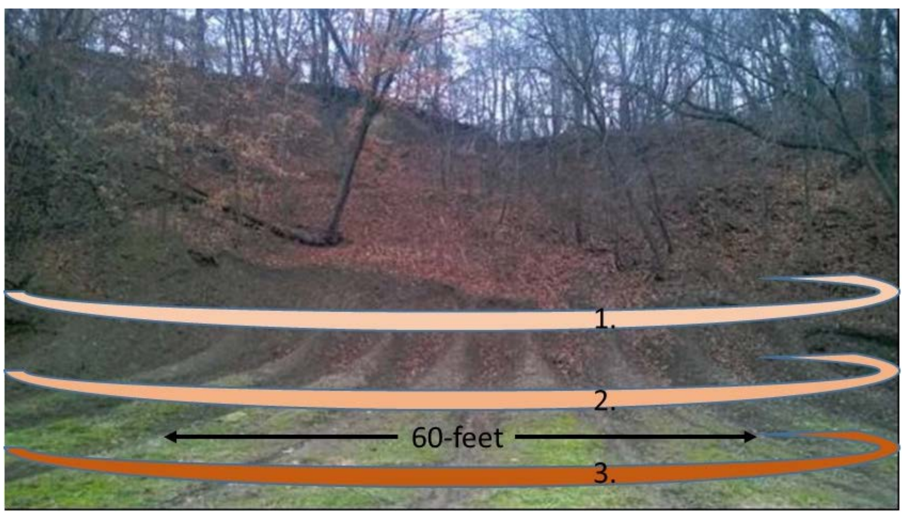

Figure 38. Center Range Hill Berm with Recommended Placement of the Flexible Reactive Berm Socks

Table 15. Schedule for Replacement of the Reactive Filter Barriers on Center Kinder Range, Fort Leavenworth.

Reactive filter barrier replacement per implementation year			
Year 1	**Year 2**	**Year 3**	**Year 4**
Barrier 1	Barrier 1	Barrier 1	Barrier 1
	Barrier 2		Barrier 2
		Barrier 3	

A more permanent solution to the challenge of heavy storm water sediment flow across the Center Kinder Range would require reduction of both the amount/velocity of storm water cascading down the firing area and the concentration of sediment in the runoff water. One option to reduce the amount/velocity of runoff water would require diversion of the storm water at the top of the hill. Another option would be construction of an “eyebrow” over the berm area so it never receives rain water. The berm area would also require some form of containment for the metal-contaminated sediment and water. The flexible reactive barriers could be used as a “slope interruption”, similar to that proposed in Figure 39. The reactive barrier filter socks would reduce the concentration of metal-contaminated sediment in the runoff water. A more costly option would be to remove part of the berm and install a bullet-trap system that could be sieved regularly in order to remove spent bullets.

In summary,

- Reactive filter barriers were successful at removing sediment from runoff water when placed according to the stormwater model developed by ERDC-EL.
- Reactive filter barriers were successful at removing Pb from runoff water when placed according to the stormwater model developed by ERDC-EL.
- Coarse sand would provide greater flow through the reactive filter barriers and decrease sediment deposits upstream of the barriers.
- Heavy metal adsorption amendments in the reactive filter barrier allow the barrier contents to pass the TCLP which reduces hazardous waste disposal costs.

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9.0 REFERENCES

American Public Health Association (APHA). 1998. *Standard methods for the examination of water and wastewater. Method 3010.*_ Andrew D. Eaton, Lenore S. Clesceri, Arnold E. Greenberg, Mary Ann H. Franson, ed., 20th ed., prepared and published jointly by American Public Health Association, American Water Works Association, Water Environment Federation, Washington DC.

Bhattarai, R., Kalita, P.K., Yatsu, S., Howard, H.R. and Svendsen, N.G. 2011. Evaluation of compost blankets for erosion control from disturbed lands. *J. Environ.Mgmt*., 92, 803-812.

Bradl, H. 2004. Adsorption of heavy metal ions on soils and soil constituents. *J. Colloid Interf. Sci*., 277, 1-18.

Chen, M., S. Daroub, L. Ma, W. Harris, and X. Cao. 2002. Characterization of lead in soils of a rifle/pistol shooting range in central Florida, USA. *Soil and Sediment Contamination* 11, 1-17.

Covelo, E.F., Vega, F.A., and Andrade, M.L. 2007. Competitive sorption and desorption of heavy metals by individual soil components, *Journal of Hazardous Materials* 140(1-2): 308-315.

Davis, A.P. and McCuen, R.H. 2005. Stormwater Management for Smart Growth. Springer Science+Business Media, Inc., New York, NY.

Dortch, M. 2013. Modeling the performance of sand filters for removing runoff suspended sediment. ERDC/EL CR-13-3, US Army Engineer Research and Development Center, Vicksburg, MS.

Faucette, L.B., J. Governo, C.F. Jordan, B.G. Lockaby, H.F. Carino, and R. Governo. 2007. Erosion control and storm water quality from straw with PAM, mulch, and compost blankets of varying particle sizes. *Journal of Soil and Water Conservation*, 62, 404-413.

Faucette, L.B., F.A. Cardoso-Gendreau, E. Codling, A.M. Sadeghi, Y.A. Pachepsky, and D.R. Shelton. 2009a. Storm Water Pollutant Removal Performance of Compost Filter Socks. *Journal of Environmental Quality*, 38:1233–1239.

Faucette, L.B., J. Governo, R. Tyler, G. Gigley, C.F. Jordan, and B.G. Lockaby. 2009b. Performance of compost filter socks and conventional sediment control barriers used for perimeter control on construction sites. *Journal of Soil and Water Conservation*, 64, 81-88.

Ford, R.G., Bertsch, P.M. and Farley, K.J. 1997. Changes in transition and heavy metal partitioning during hydrous iron oxide aging. *Environ. Sci. Technol*., 31, 2028-2033.

Han, R., Lu, Z., Zou, W., Daotong, W., Shi, J., and Jiujun, Y. 2006. Removal of copper(II) and lead(II) from aqueous solution by manganese oxide coated sand. II. Equilibrium study and competitive adsorption. *J. Haz. Mats.*, 137, 480-488.

Komárek, M., Vaněk, A. and Ettler, V. 2013. Chemical stabilization of metals and arsenic in contaminated soils using oxides – A review. *Environmental Pollution*, 172, 9-22.

Larson, S., B. Tardy, M. Beverly, A. Hearn, M. Thompson, and G. Williams. 2004. *Topical application of phosphate amendments to lead-contaminated small arms firing range soils.* ERDC/EL TR-03-20. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Larson, S.L., B. Tardy, K. Rainwater, and J.S. Tingle. 2005. *Rainfall lysimeter evaluation of leachability and surface transport of heavy metals from six soils with and without phosphate amendment*. ERDC TR-05-9, US Army Engineer Research and Development Center, Vicksburg, MS.

Larson, S.L., Davis, J.L., Martin, W.A., Felt, D.R., Nestler, C.C., Brandon, D.L., Fabian, G., and O'Connor, G. 2007a. *Grenade range management using lime for metals immobilization and explosives transformation.* ERDC/EL TR-07-5, US Army Engineer Research and Development Center, Vicksburg, MS.

Larson, S.L., P.G. Malone, C.A. Weiss, W.A. Martin, C. Trest, G. Fabian, M.F. Warminsky, D. Mackie, J.J. Tasca, J. Wildey, and J. Wright. 2007b. *Amended ballistic sand studies to provide low maintenance lead containment at an active small arms firing range systems*. ERDC/EL TR-07-14, US Army Engineer Research and Development Center, Vicksburg, MS.

Larson, S.L., C.L. Teeter, V.F. Medina and W.A. Martin. 2007c. *Treatment and management of closed or inactive small arms firing ranges*. ERDC/EL TR-07-6. US Army Engineer Research and Development Center, Vicksburg, MS.

Larson, S. L., Griggs, C., Ballard, J. and Waggoner, C. 2011. Fishbone, a biogenic apatite, for sustainable remediation of uranium-contaminated water. *Proceedings of the Conference onWaste Management*, Paper #11534, Phoenix, AZ, March 7-11, 2011.

Larson, S.L., W.A. Martin, M. Dortch, C.C. Thomas, C.S. Griggs and C. Nestler. 2016, in press. *Flexible Reactive Berm (FRBerm) for Removal of Heavy Metals from Runoff Water. Treatability Study*. ERDC/EL TR-16-xx, US Army Engineer Research and Development Center, Vicksburg, MS.

Martin, W.A., S.L. Larson, D.R. Felt, J. Wright, C.S. Griggs, M. Thompson, J.L. Conca, C.C. Nestler. 2008. The effect of organics on lead sorption onto Apatite II™. *Appl. Geochem*., 23, 34-43.

Martinez, C.E. and McBride, M.B. 1998. Solubility of Cd^{2+}, Cu^{2+}, Pb^{2+}, and Zn^{2+} in aged coprecipitates with amorphous iron hydroxides. *Environ. Sci. Technol*., 32, 743-748.

Martinez, C.E., Sauve, S., Jacobsen, A. and McBride, M.B. 1999. Thermally induced release of adsorbed Pb upon aging ferrihydrite and soil oxides. *Environ. Sci. Technol*., 33, 2016-2020.

Ndiba, P., Axe, L., and Boonfueng, T. 2008. Heavy metal immobilization through phosphate and thermal treatment of dredged sediments. *Environ. Sci. Technol*., 42, 920-926.

O'Connor, G., Larson, S.L., Weiss, C., Jr., Malone, P/. Price, R.A., Batchelor, C., Capuano, C., Foote, C., Thompson, M., Powell, K., Beverly, M., Valentin, M., Williams, G., Trest, C., McGhee, C. and Parsons, H. 2007. Small arms range use of tungsten and lead bullets: Behavior of metals in range soils. Report prepared for US Army Armament Research, Development and Engineering Center (ARDEC), Picatinny, NJ.

Orsetti, S., de las Mercedes, Quiroga, M., and Andrade, E.M. 2006. Binding of Pb(II) in the system humic acid/goethite at acidic pH. *Chemosphere*, 65, 2313-2321.

O'Toole, M. J. 1994. *Technical and administrative guidance memorandum #4046: Determination of soil cleanup objectives and cleanup levels.* New York State Department of Environmental Conservation.

Parsons Engineering Science, Inc., Final Treatability Study in Support of Remediation by Natural Attenuation at Site 9431-F at Fort Jackson South Carolina, June 1999.

Shacklette, H.T. and J.G. Boerngen. 1984. *Element concentrations in soils and other surficial materials of the conterminous United States*. U.S. Geological Survey Professional Paper 1270

Tardy, N.A., Bricka, R.M., and Larson, S.L. 2003. *Chemical stabilization of lead in small arms firing range soils.* ERDC/EL TR-03-20, US Army Engineer Research and Development Center, Vicksburg, MS.

Trivedi, P. and Axe, L. 2000. Modeling Cd and Zn sorption to hydrous metal oxides. *Environ. Sci. Technol*., 34, 2215-2223.

U.S. Army Aberdeen Test Center (ATC). 2009. *Report for the Small Arms Range Environmental Best Management Practice (BMP) Demonstration: Targeted Lead Removal to Control Lead Migration.* Report No. ATC-9816, U.S. Army Aberdeen Test Center, Aberdeen Proving Ground, MD.

United States Environmental Protection Agency (USEPA). 1999a. *Test methods for evaluating solid waste, physical/chemical methods.* SW-846. Washington, DC.

United States Environmental Protection Agency (USEPA). 1999b. *Understanding variation in partition coefficient, K_d values. Volume 1. The K_d model, methods of measurement, and application of chemical reaction codes.* EPA 402-R-99-004A. U.S. Environmental Protection Agency, Washington, DC.

United States Environmental Protection Agency (USEPA). 2006. *National pollutant discharge elimination system (NPDES) national menu of stormwater best management practices. Construction site stormwater runoff control: Compost filter socks.* Available at: http://fpub.epa.gov/npdes/stormwater/menuofbmps/compost filtersock.cfm

(accessed 22 Feb. 2008; verified 6 Feb. 2009). U.S. Environ. Protection Agency, Washington, DC.

United States Environmental Protection Agency (USEPA). 2012. Stormwater Best Management Practice: *Silt Fences*. EPA 833-F-11-008. Available at: http://www.epa.gov/npdes/pubs/siltfences.pdf

Wynter, M., S.L. Larson, W.A. Martin, C.S. Griggs, G. O'Connor, D. Mackie, C.C. Nestler. 2012. *Passive reactive berm to provide low maintenance lead containment at active small arms firing ranges. Field Demonstration*. ERDC/EL TR-12-20, Engineering Research and Development Center, Vicksburg, MS.

APPENDIX A POINTS OF CONTACT

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Jeff Sylva	GSI Pacific, Inc.		Construction and assembly of filter barriers

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APPENDIX B SAMPLING METHODS

Samples were labeled and tightly sealed to avoid cross-contamination during storage and/or shipment. A sample identification system was followed to ensure tracking of a sample through collection, analysis, data validation and data reduction. Each identification label was unique within this demonstration project and based on field identities of each sampling site as indicated on Figures 22 and 24 in this report (Section 5.5). For example, SS-1-1 refers to a sediment sample, taken in front of Sock 1, sample #1; FMS-1-1 refers to a filter media sample taken from within sock 1, sample #1.

Samples were not taken during the field demonstration itself, but during the system shutdown and demobilization phase. Entire filter socks were drummed and mailed to the ERDC-EL HWRC. Sediment samples were mailed to ERDC-EL HWRC in coolers. All remaining demonstration material was returned to the HWRC in labeled 55-gal drums. Field logbooks were kept by the subcontractor on this field demonstration, Alion, Inc. Monthly reports documented progress on the project.

Sample analysis was performed by ERDC-EL Chemistry Branch and their sub-contractor, Pace Analytical of Lenexa, KS. Quality Control (QC) samples were analyzed and included method blanks, matrix spike and matrix spike duplicate samples.

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APPENDIX C RESPONSE TO REVIEWER COMMENTS

1. **General Comment.** While the reports address the performance metric with respect to amendment effectiveness as it relates to passing the TCLP metals regulatory requirements, it does not address the performance metrics with respect to: (i) concentration reductions of heavy metals in run-off, (ii) concentration reduction of TSS in run-off, (iii) maintenance of TOC and nutrient levels to prevent eutrophication, and (iv) life cycle cost assessments. These four objectives are critical to evaluate the success of the technology and to enable the technology transfer at DoD and commercial sites. The apparent lack of funding was used as a rationale to not satisfy these critical objectives which are essential for evaluating the success of this technology demonstration. Please comment on how the lack of these critical information at this stage will affect the technology transfer and ultimate commercialization and adoption of this technology at future DoD and non-DoD sites.

Response: The lack of critical information on runoff water characterization over time from the Fort Leavenworth project has not hampered the technology transfer to DOD sites. This information gap has been addressed in the time since the project at Fort Leavenworth was shut down and demobilized. The contractor in charge of the Leavenworth field demonstration was requested (C. Fey, Army Environmental Command) to set up a similar project on a Fort Jackson, SC, firing range (Figure 1). That demonstration was mobilized on April 26, 2016. The project included the expense of runoff water samplers and sample analysis (Figure 2). Information gained from this second, on-going, field project continues to refine the filter barrier technology.

Figure 1. Reactive filter barrier technology being used at Fort Jackson, SC

Figure 2. Automatic Runoff Water Samplers Installed at Fort Jackson, SC

2. **General Comment.** As a follow on comment to Comment 1, please provide a concise description of next steps and/or data gaps that need to be addressed for successful adoption of this technology.

Response: The data gaps are being filled through runoff water sample collection and analysis from the on-going field project at Fort Jackson, SC where this technology has been successfully adopted.

3. **Cost Assessment.** Provide some discussion on life cycle costs for this technology.

Response: Please see Table 13 of the Final report (Table 9 of the Cost & Performance report). This Table reviews the cost per linear foot of the reactive barrier and the overhaul schedule as determined by the installation contractor. As we reported in Sections 7.2 and 7.4 of the Final Report, it was actually the amount of contaminated sediment in the runoff water that determined the longevity of the filter socks. The reactive barrier amendment was able to adsorb the heavy metals in the runoff water. The stormwater runoff water model developed at ERDC-EL correctly indicated overhaul times that depend on soil type (sediment fines) and amount of precipitation.